EXHIBIT 16

US006978062B2

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Rose et al.

(10) **Patent No.: US 6,978,062 B2**
(45) **Date of Patent: Dec. 20, 2005**

(54) **WAVELENGTH DIVISION MULTIPLEXED DEVICE**

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(73) Assignee: **Ibsen Photonics A/S**, Farum (DK)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 134 days.

(21) Appl. No.: **09/790,144**

(22) Filed: **Feb. 21, 2001**

(65) **Prior Publication Data**

US 2002/0154855 A1 Oct. 24, 2002

(51) **Int. Cl.**^{7} **G02B 6/28**
(52) **U.S. Cl.** **385/24**; 385/15; 385/16; 385/39; 385/40; 359/114; 359/115; 359/124
(58) **Field of Search** 385/24, 39, 40, 385/15, 16; 359/114, 115, 124

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Primary Examiner—Tarifur R. Chowdhury
Assistant Examiner—George Y. Wang
(74) *Attorney, Agent, or Firm*—Altera Law Group, LLC

(57) **ABSTRACT**

A wavelength division multiplexed device is based on a transmission grating spectrometer having at least two diffractive optical elements. The WDM device provides flexible use and may be widely applied in WDM systems. The device is useful for multiplexing and demultiplexing, channel monitoring, and for adding and dropping channels. The device provides programmability in use as an add/drop multiplexer.

80 Claims, 25 Drawing Sheets

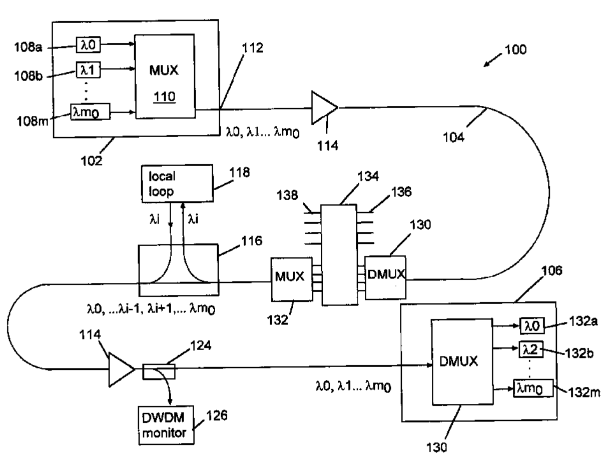
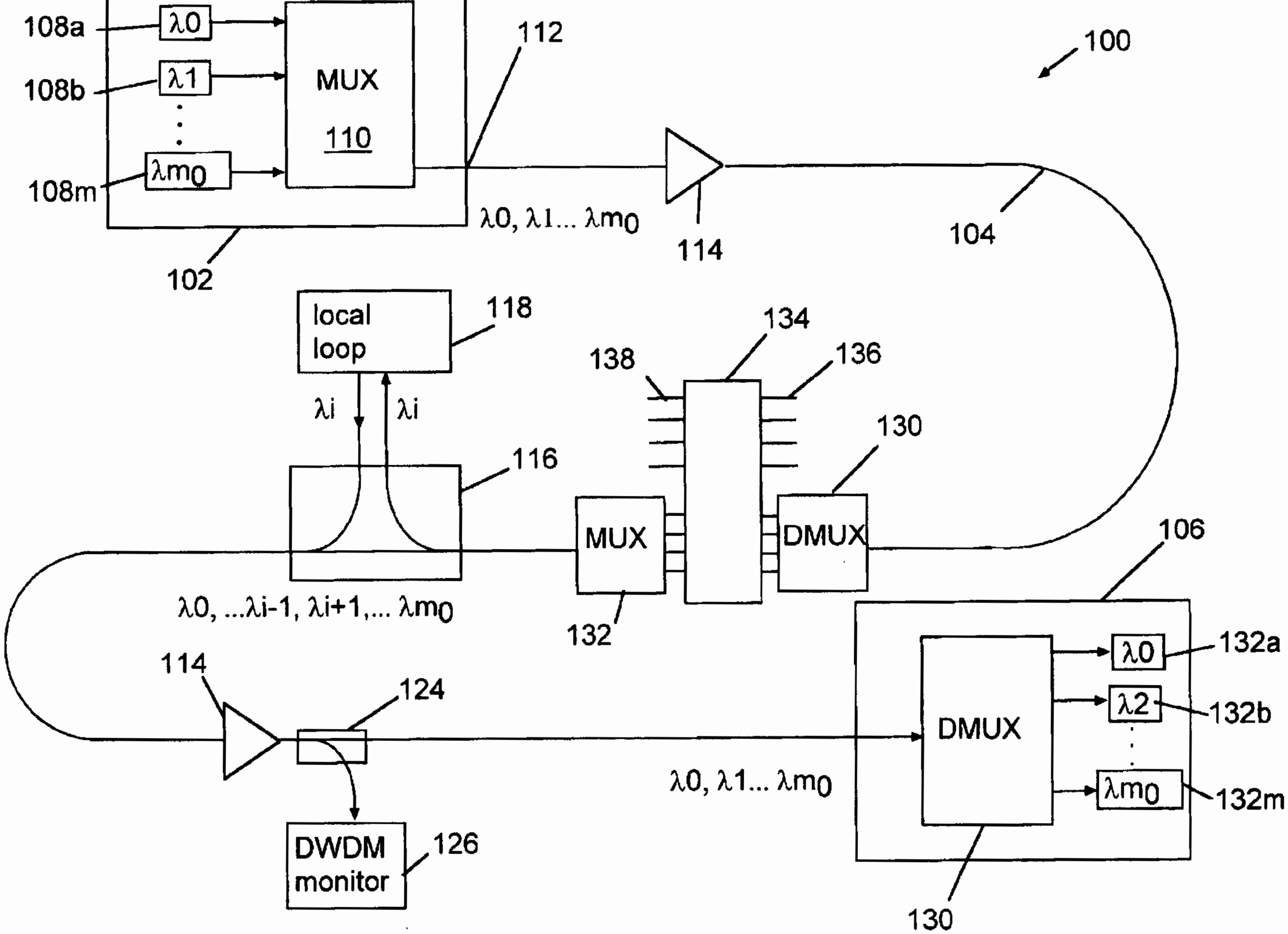


FIG. 1


100
108a
108b
108m
λ0
λ1
λm0
MUX
110
112
λ0, λ1... λm0
114
104
102
local loop
118
λi
λi
116
134
138
136
130
MUX
DMUX
106
λ0, ...λi-1, λi+1,... λm0
132
114
124
DMUX
λ0
λ2
λm0
132a
132b
132m
λ0, λ1... λm0
DWDM monitor
126
130

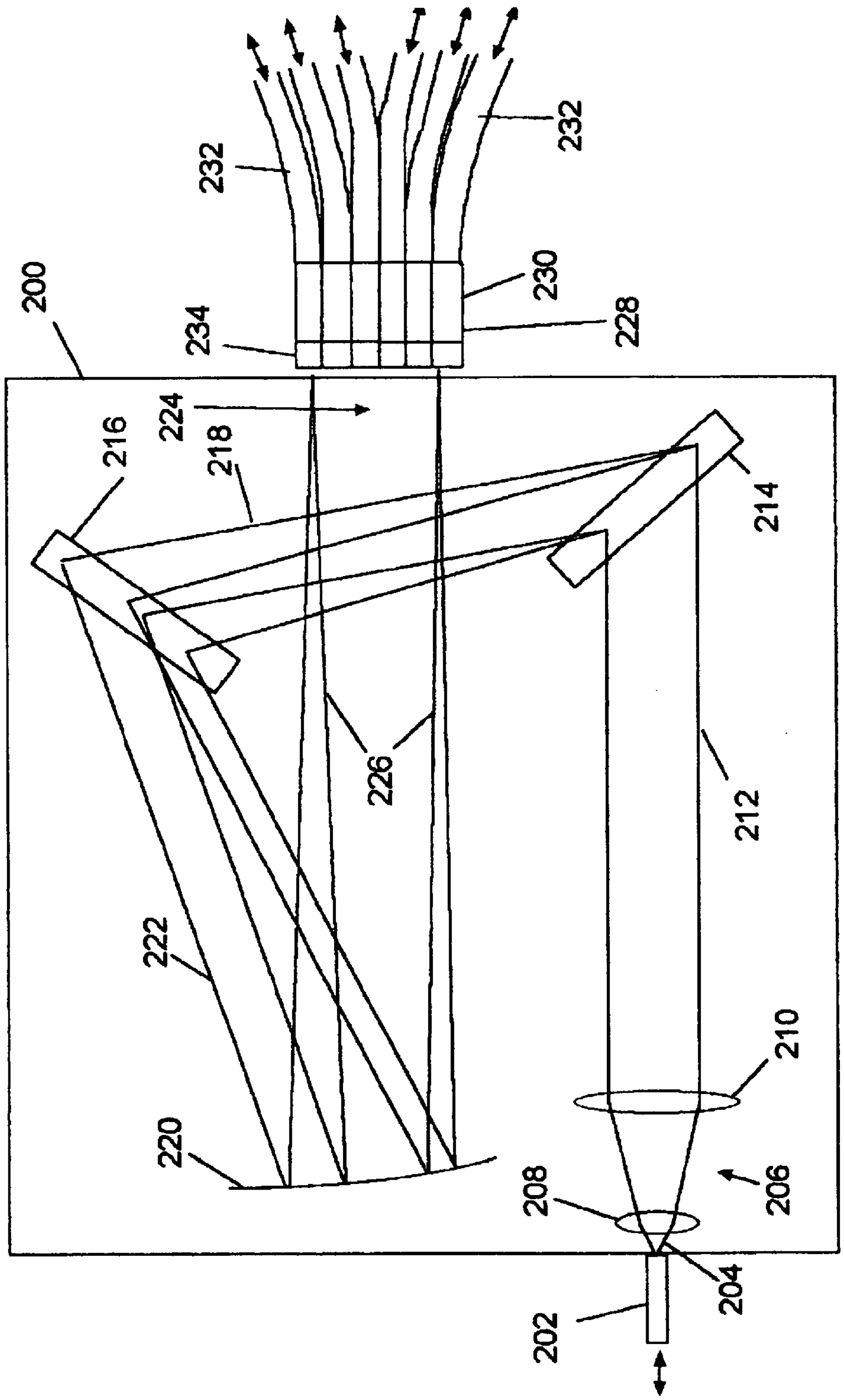

232
232
200
234
230
228
224
216
218
214
226
212
222
210
220
208
206
204
202

FIG. 2

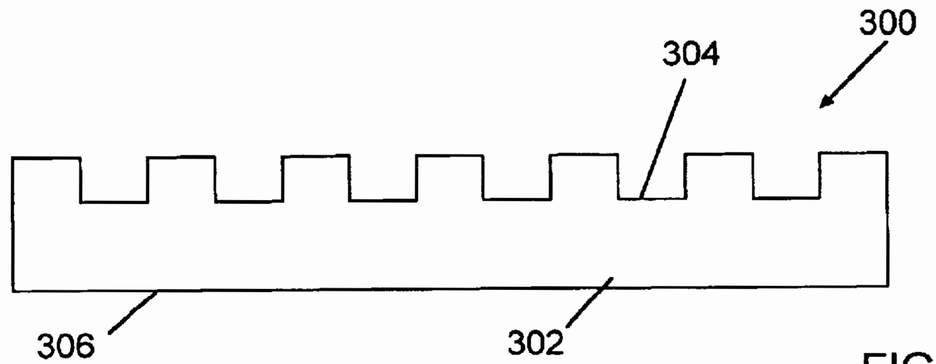


FIG. 3

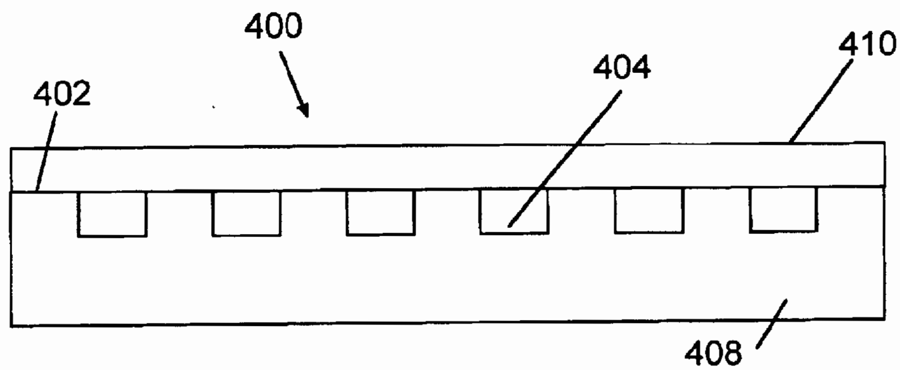


FIG. 4

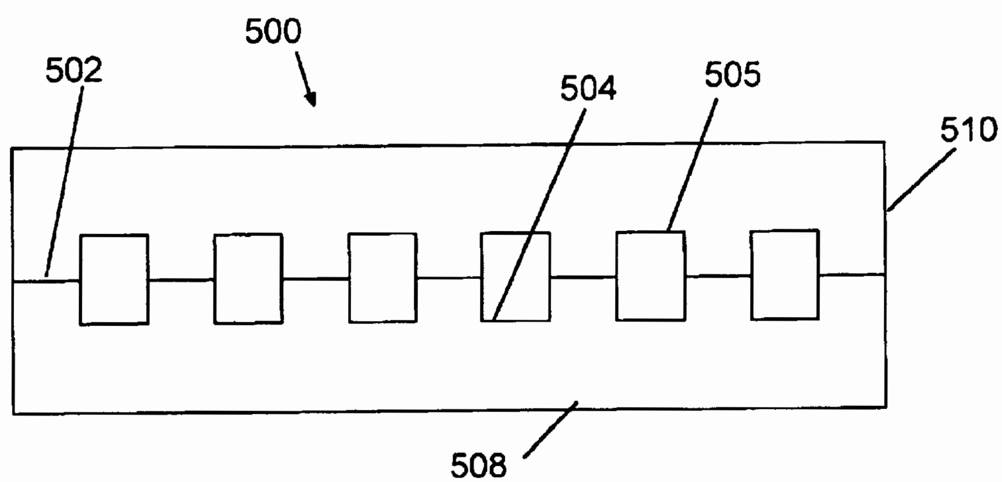


FIG. 5

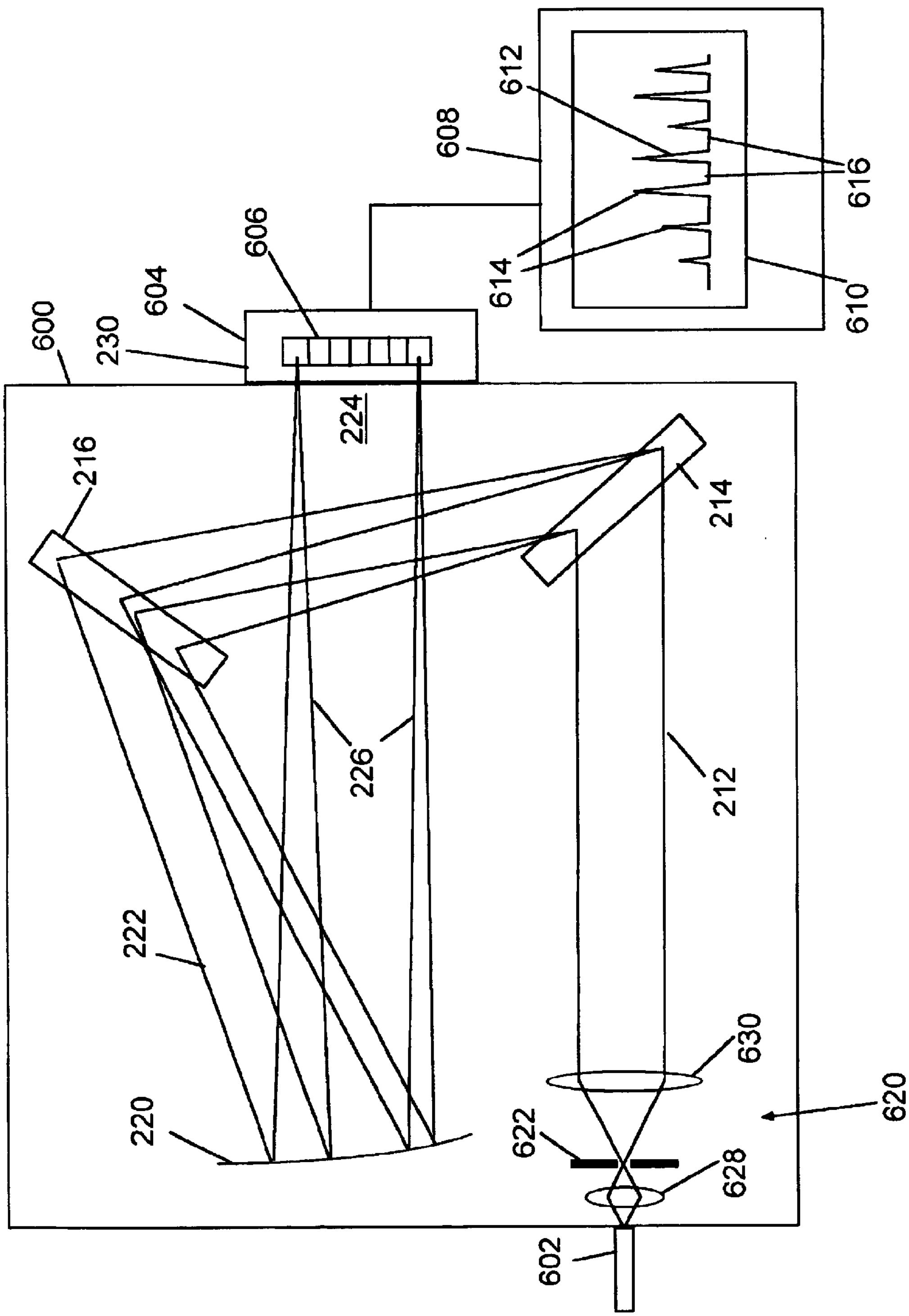
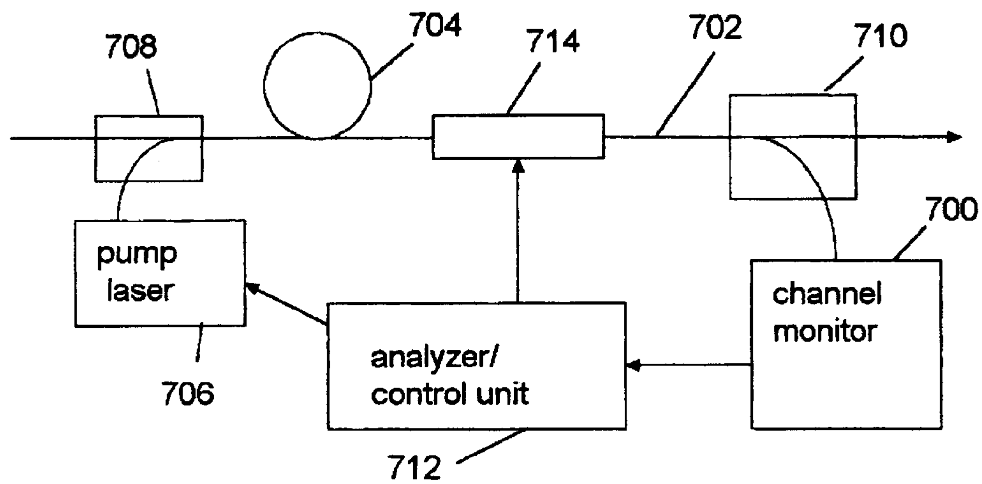
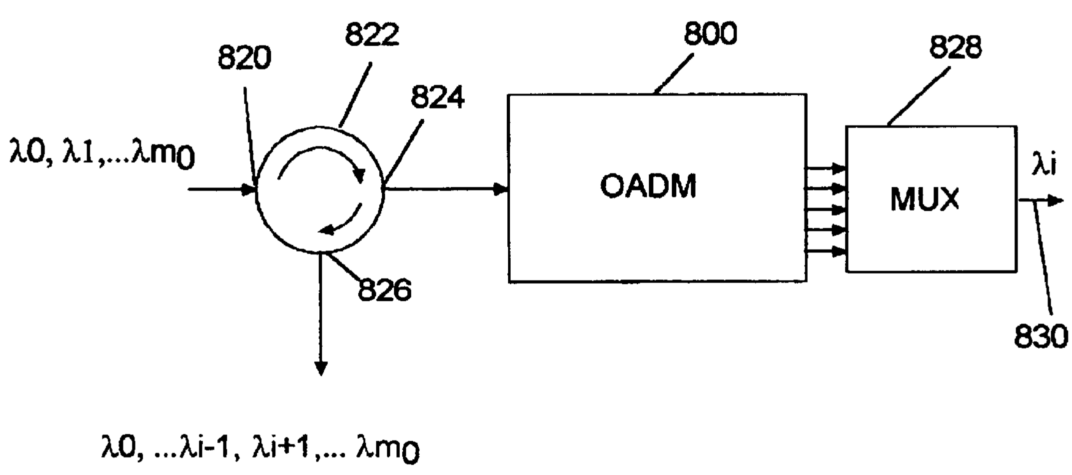

600
230
604
606
608
612
614
616
610
224
216
214
226
212
222
630
620
220
622
628
602

FIG. 6



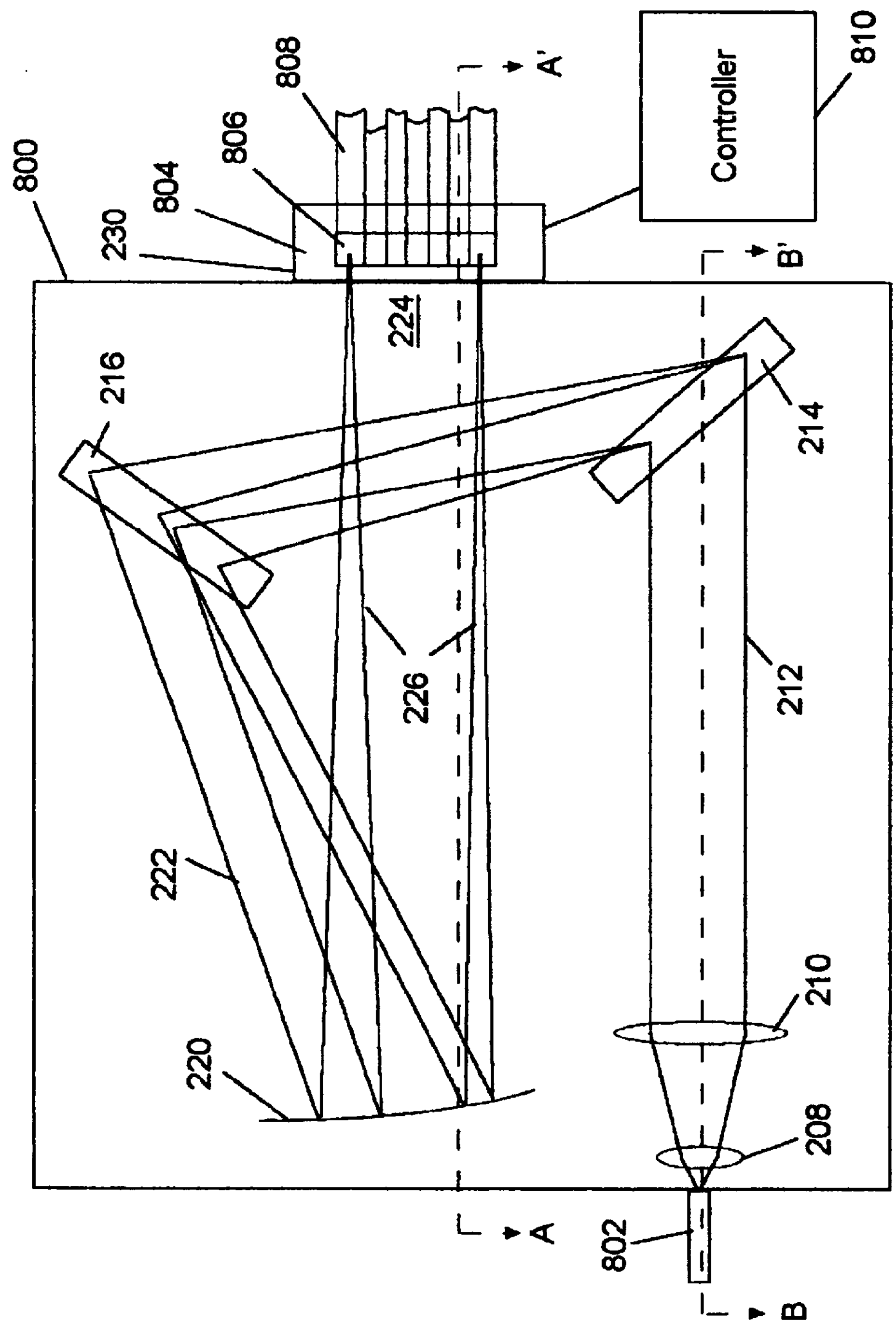
708
704
714
702
710
700
pump laser
channel monitor
analyzer/ control unit
706
712

FIG. 7



820
822
824
800
828
λ0, λ1,...λm0
OADM
MUX
λi
826
830
λ0, ...λi-1, λi+1,... λm0

FIG. 10



Controller
810
808
806
804
800
230
224
216
214
226
222
212
220
210
208
802
A'
B'
A
B

FIG. 8

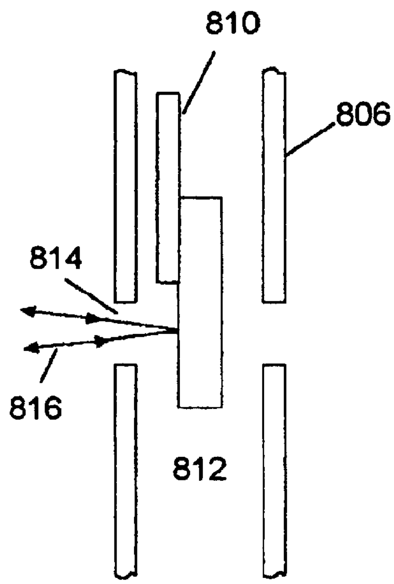


FIG. 9A

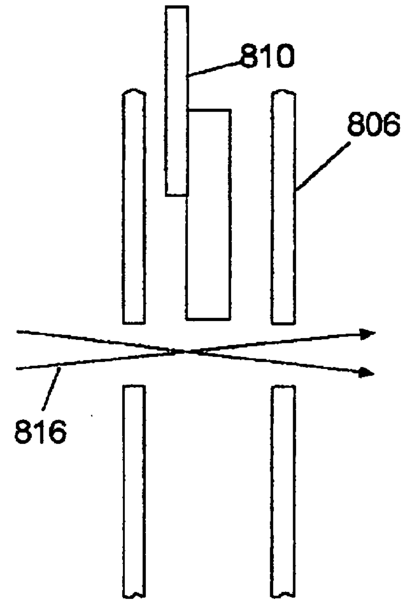


FIG. 9B

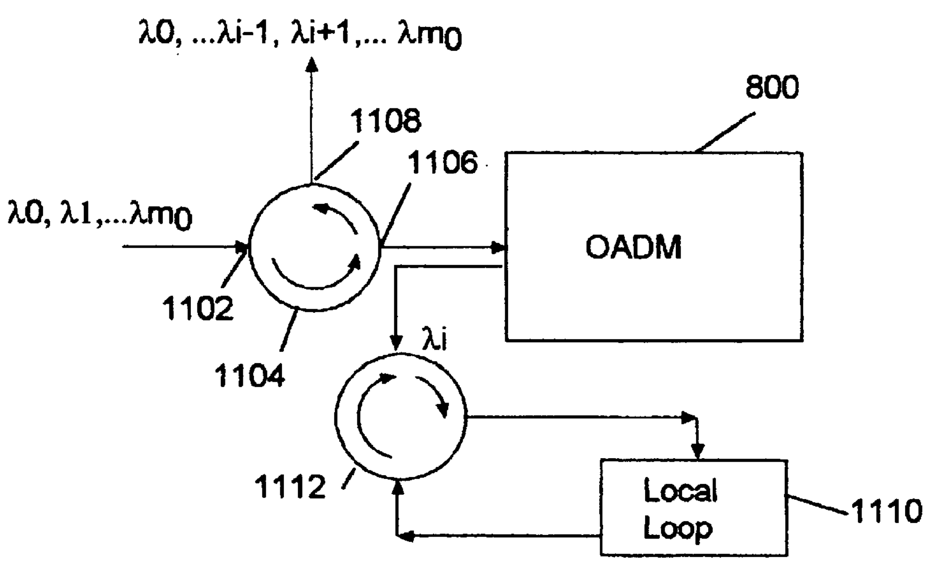


FIG. 11

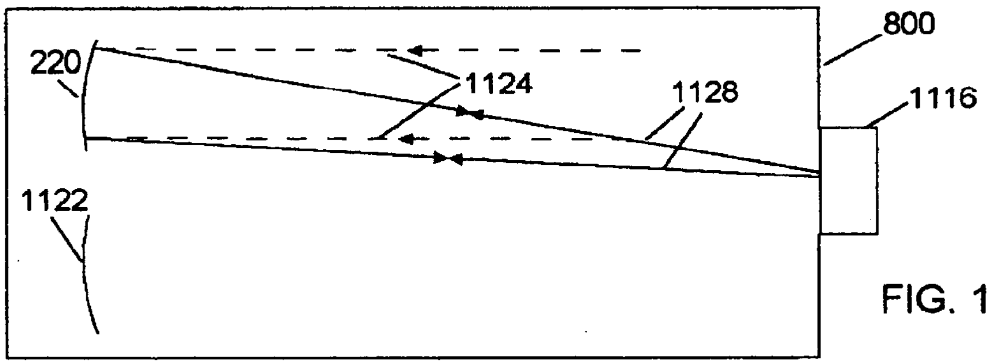


FIG. 12A

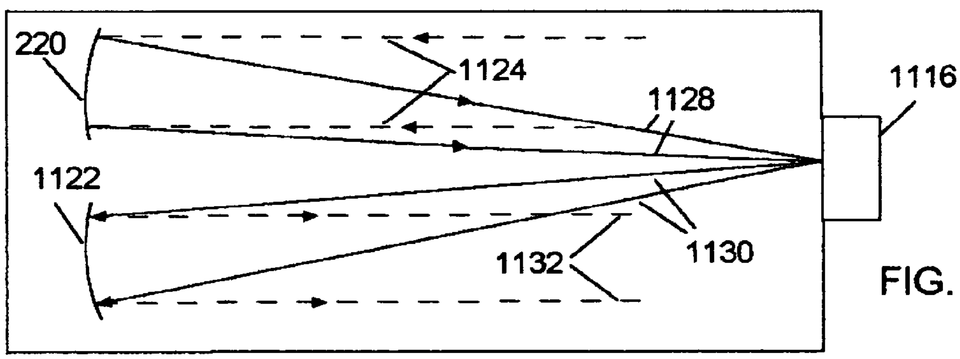


FIG. 12B

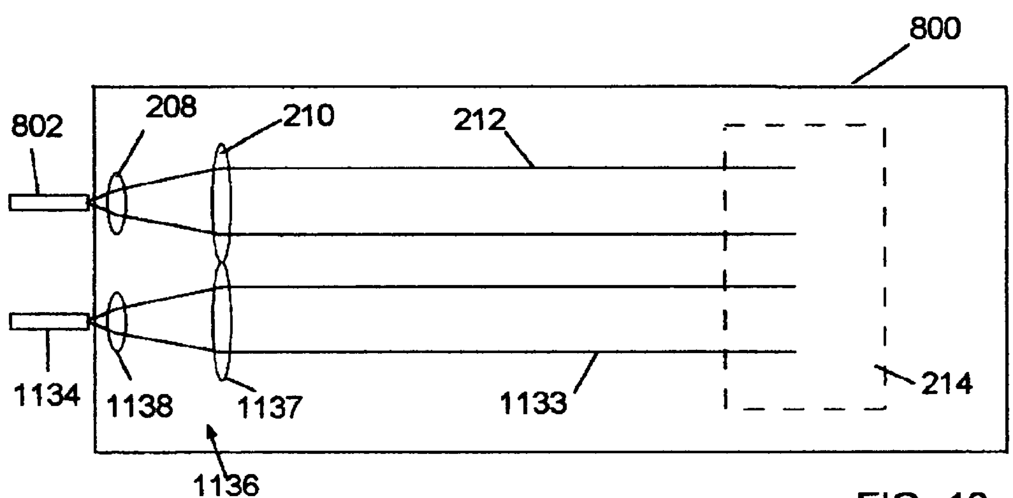


FIG. 13

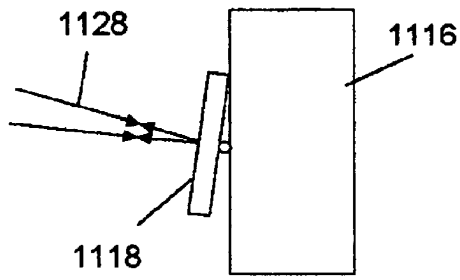


FIG. 14A

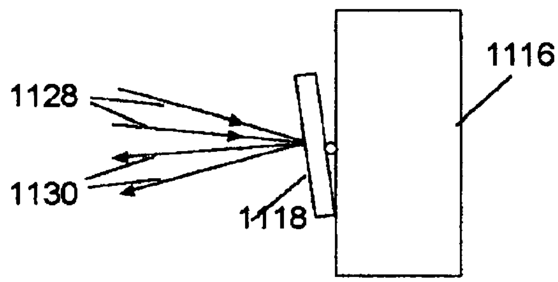


FIG. 14B

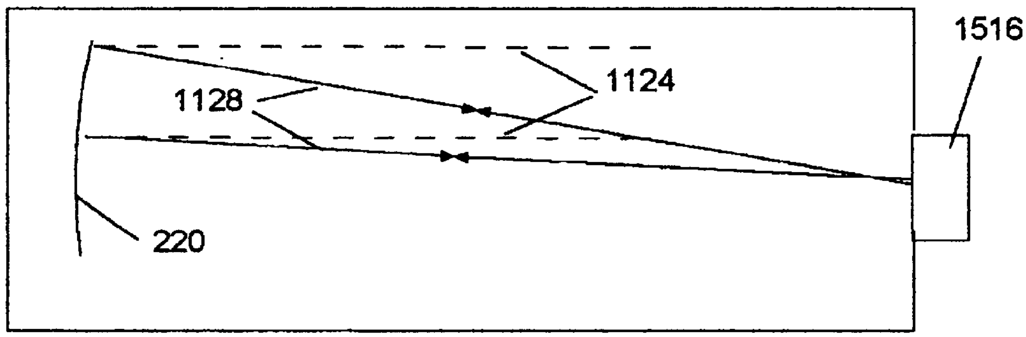


FIG. 15A

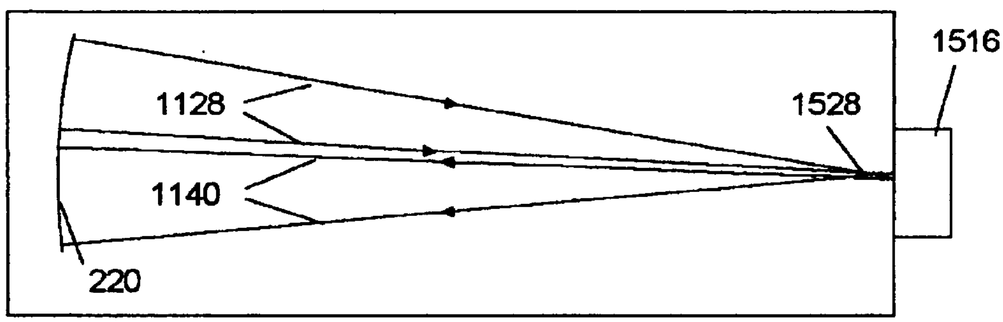


FIG. 15B

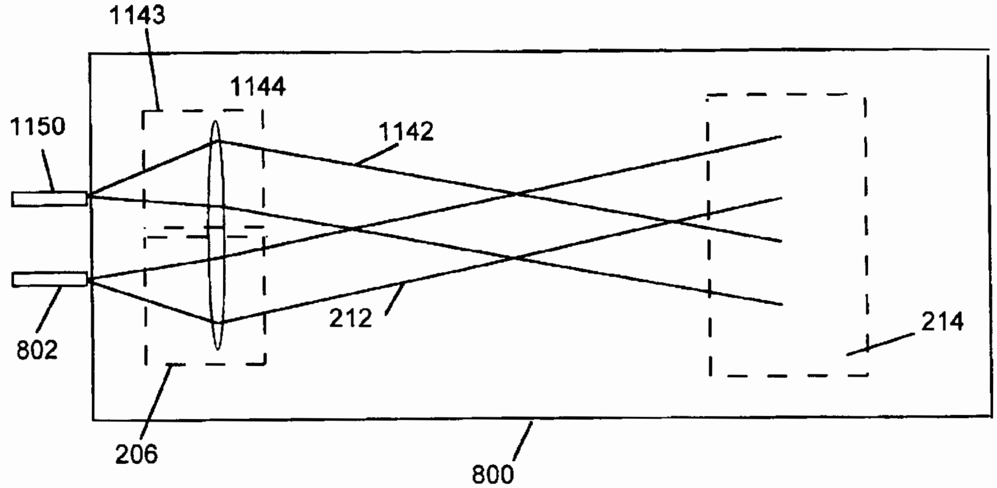


FIG. 16

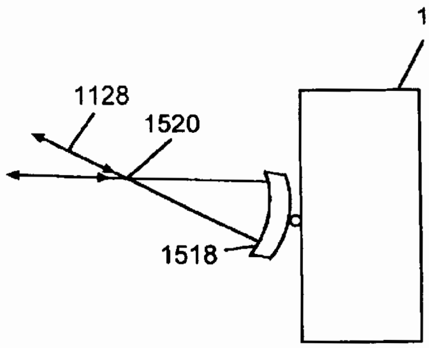


FIG. 17A

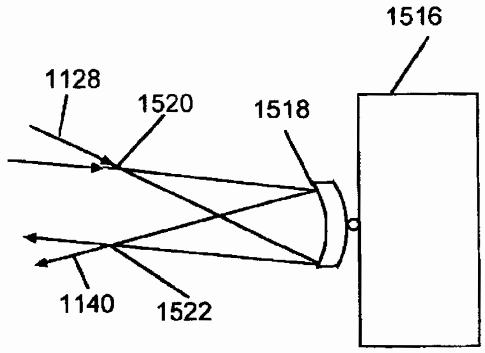


FIG. 17B

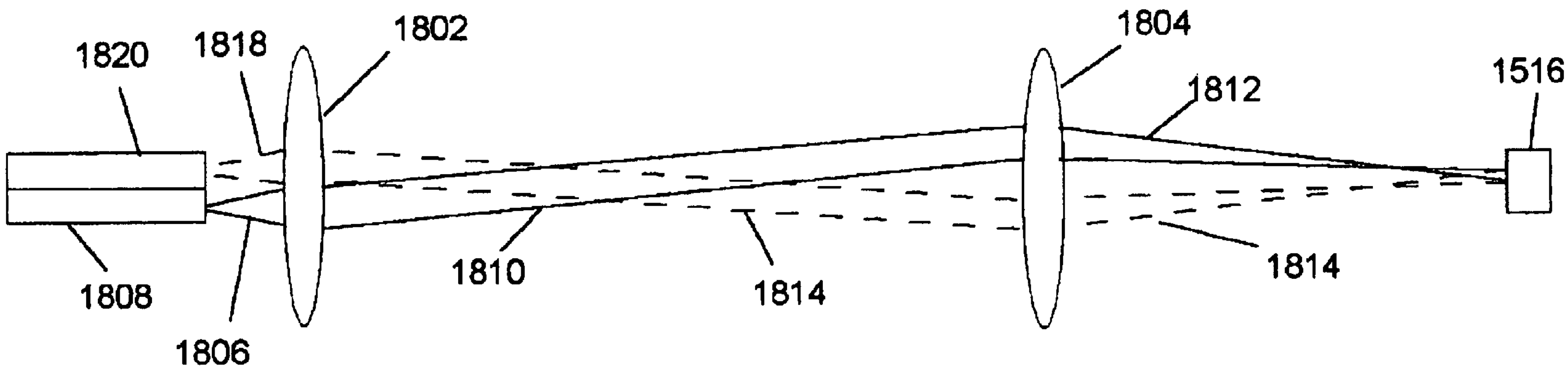


FIG. 18A

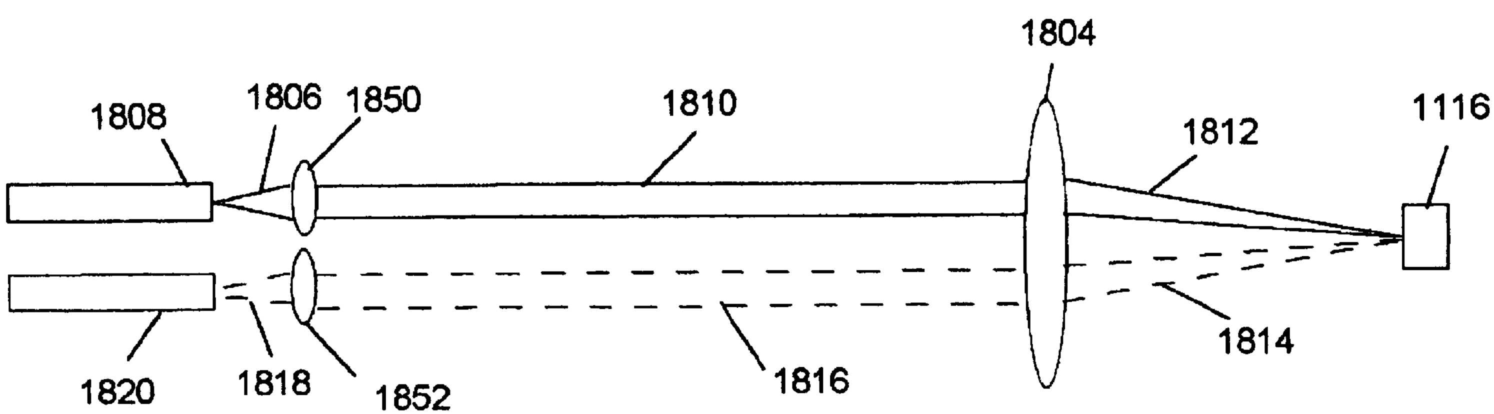


FIG. 18B

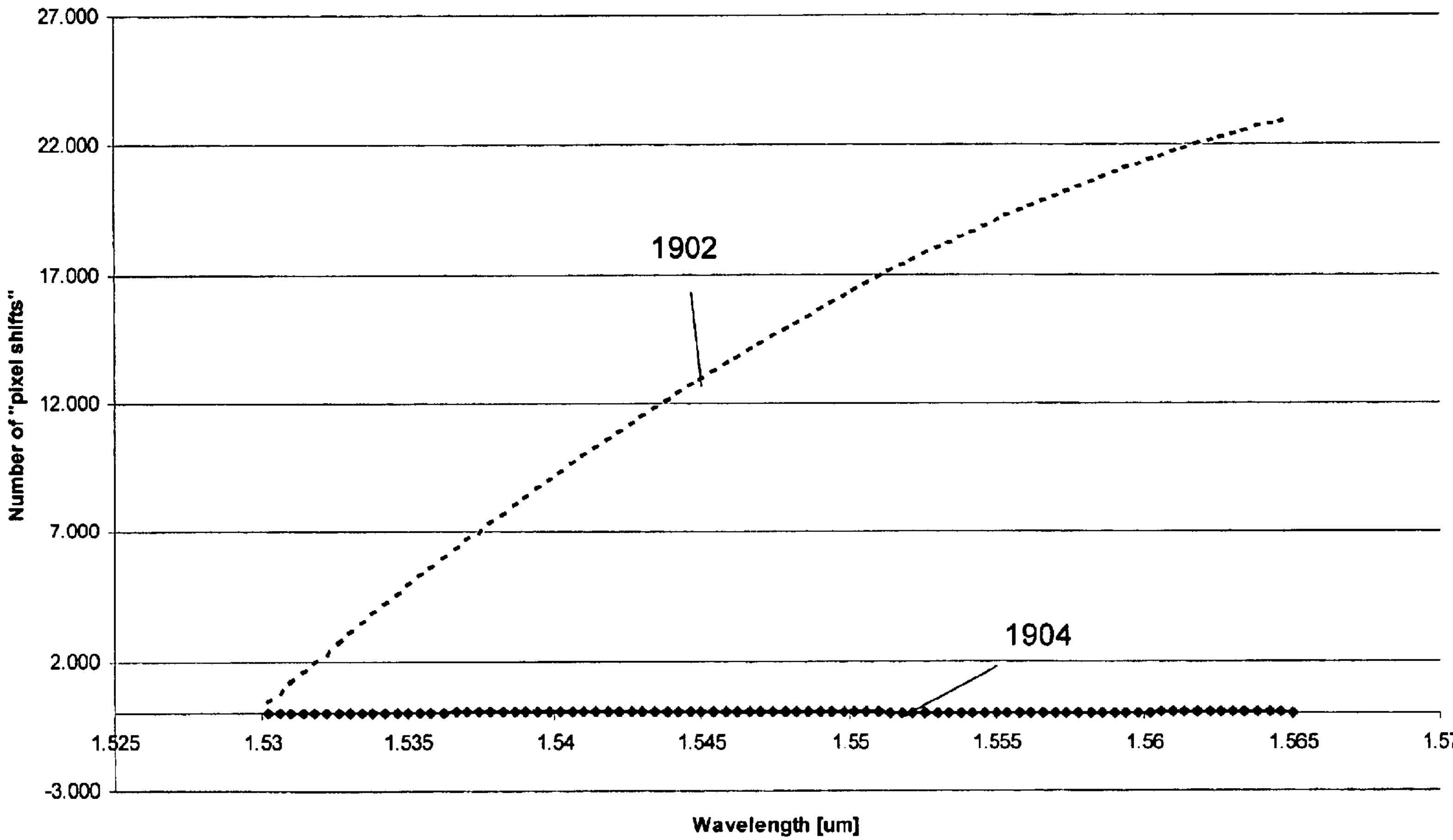

Number of "pixel shifts"
27.000
22.000
17.000
12.000
7.000
2.000
-3.000
1.525
1.53
1.535
1.54
1.545
1.55
1.555
1.56
1.565
1.57
Wavelength [um]
1902
1904

FIG. 19

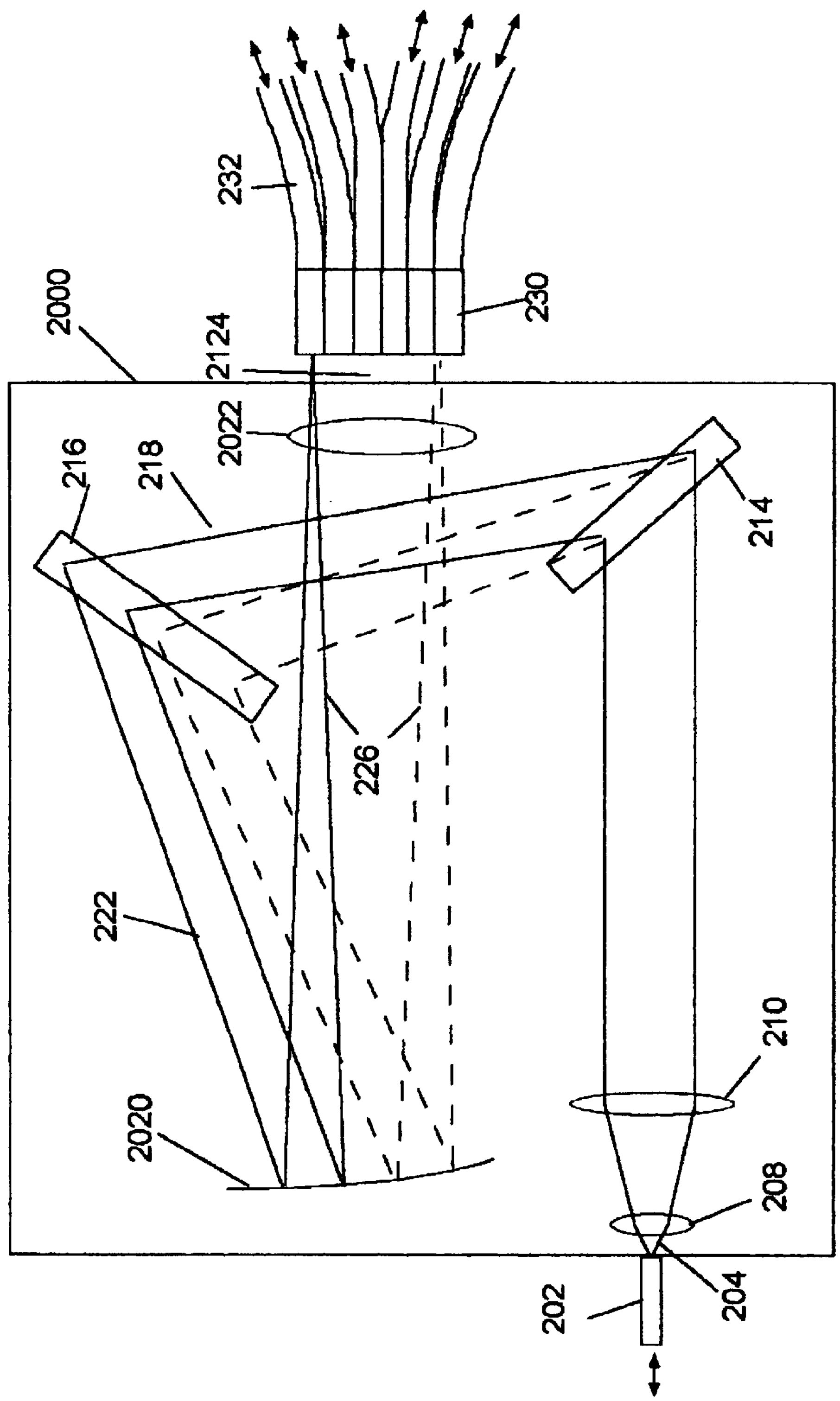


FIG. 20

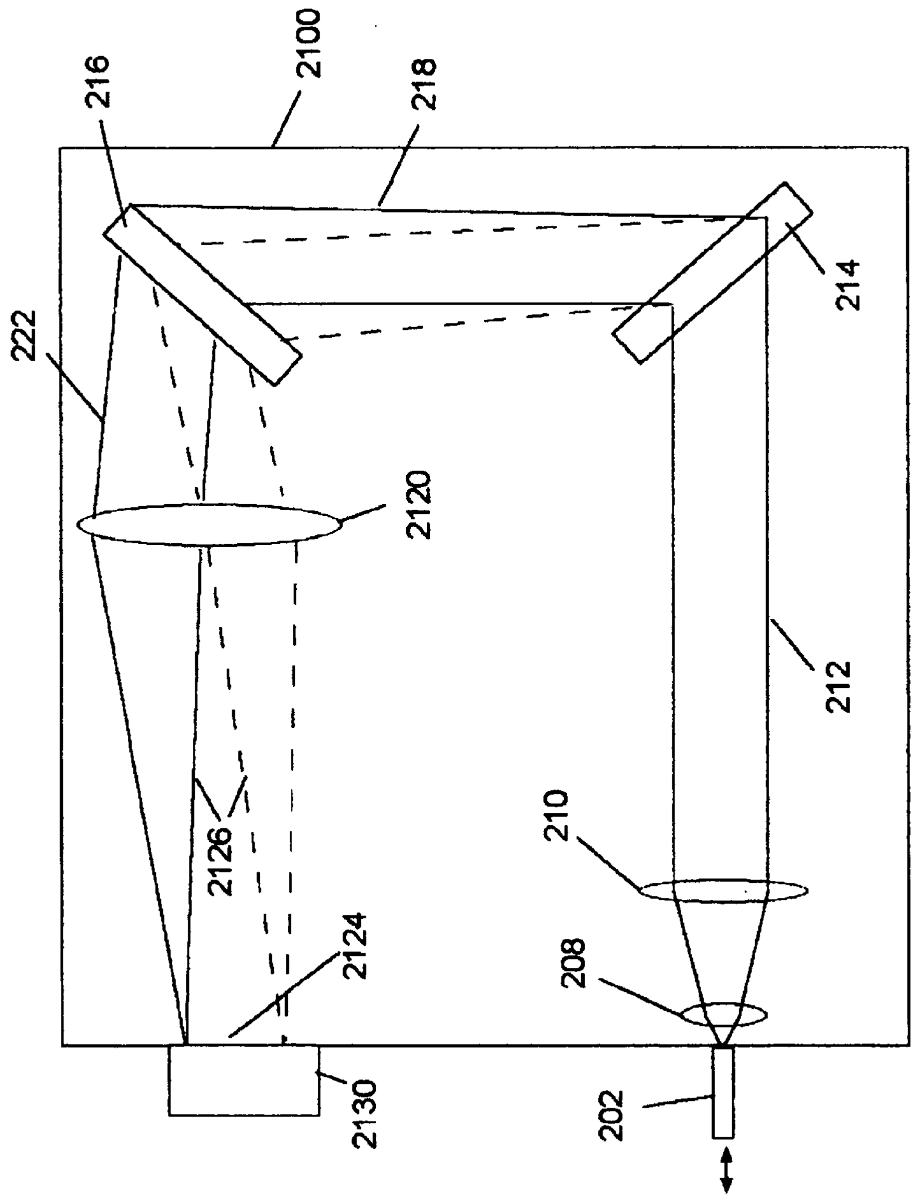


FIG. 21

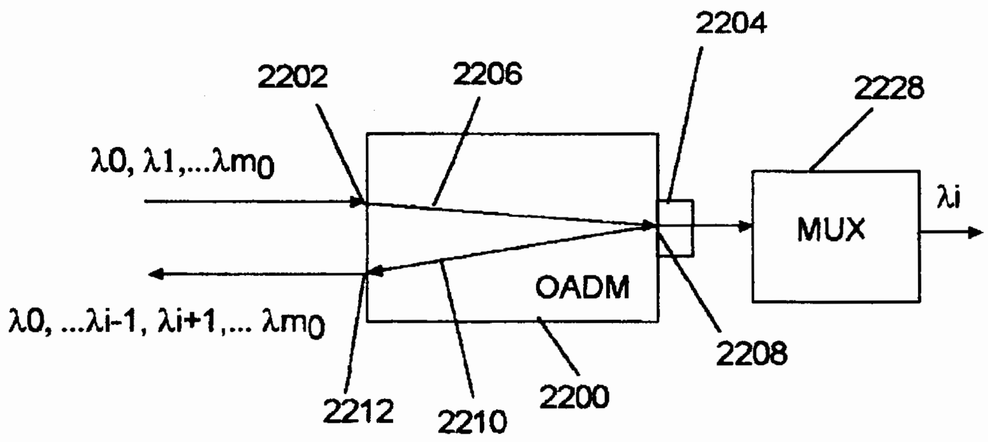

2204
2202
2206
2228
λ0, λ1,...λm0
λi
MUX
OADM
λ0, ...λi-1, λi+1,... λm0
2208
2200
2212
2210

FIG. 22

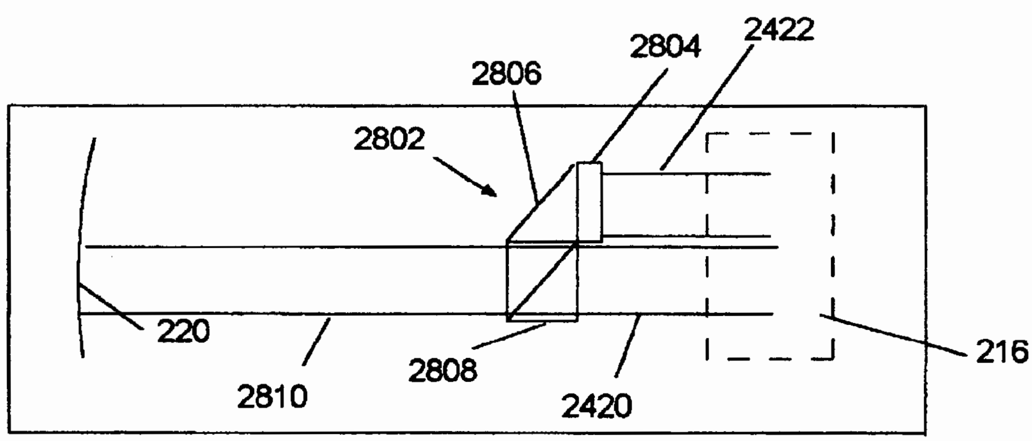
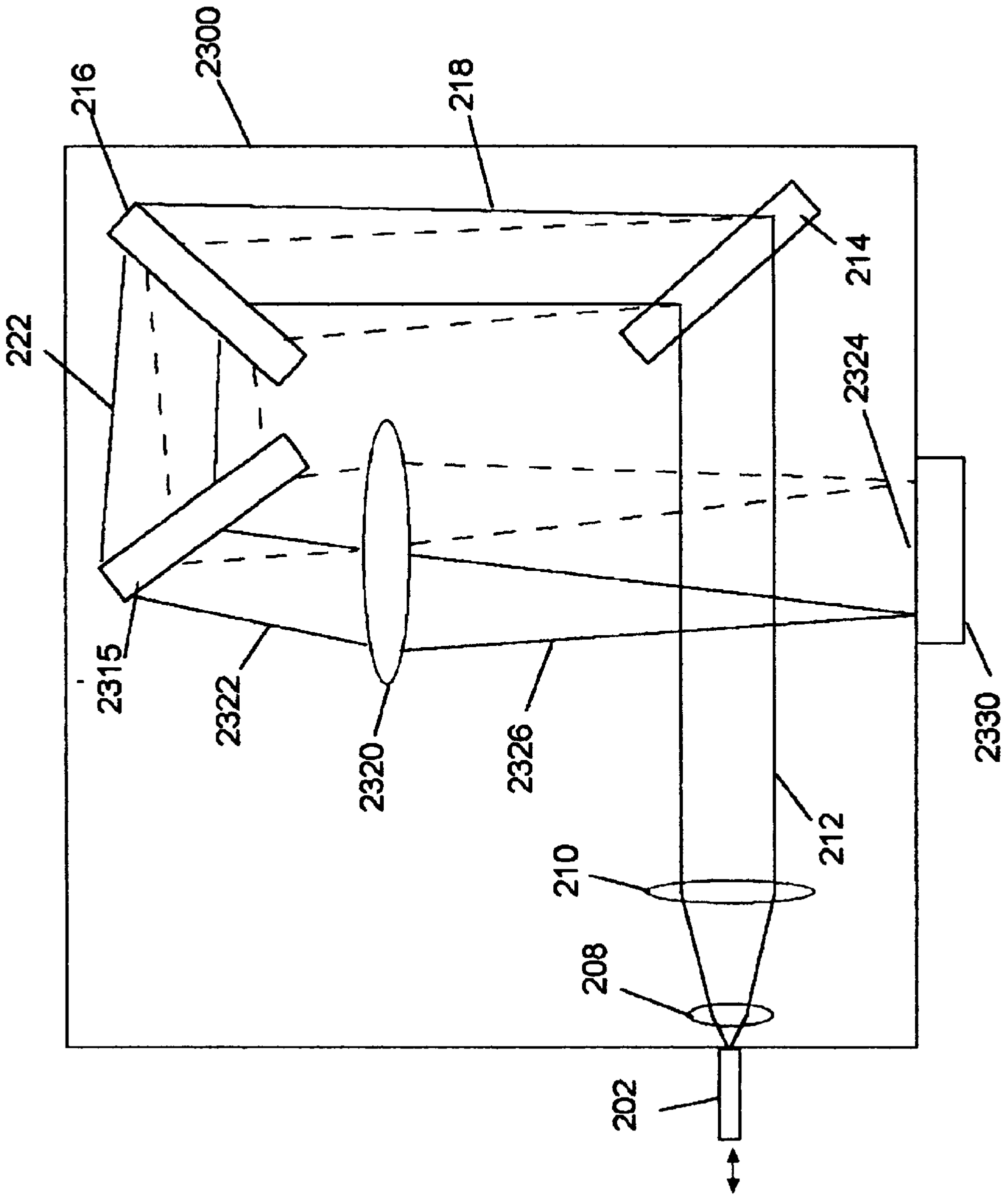

2422
2804
2806
2802
220
2810
2808
2420
216

FIG. 29



216
2300
218
214
222
2324
2315
2322
2320
2326
2330
212
210
208
202

FIG. 23

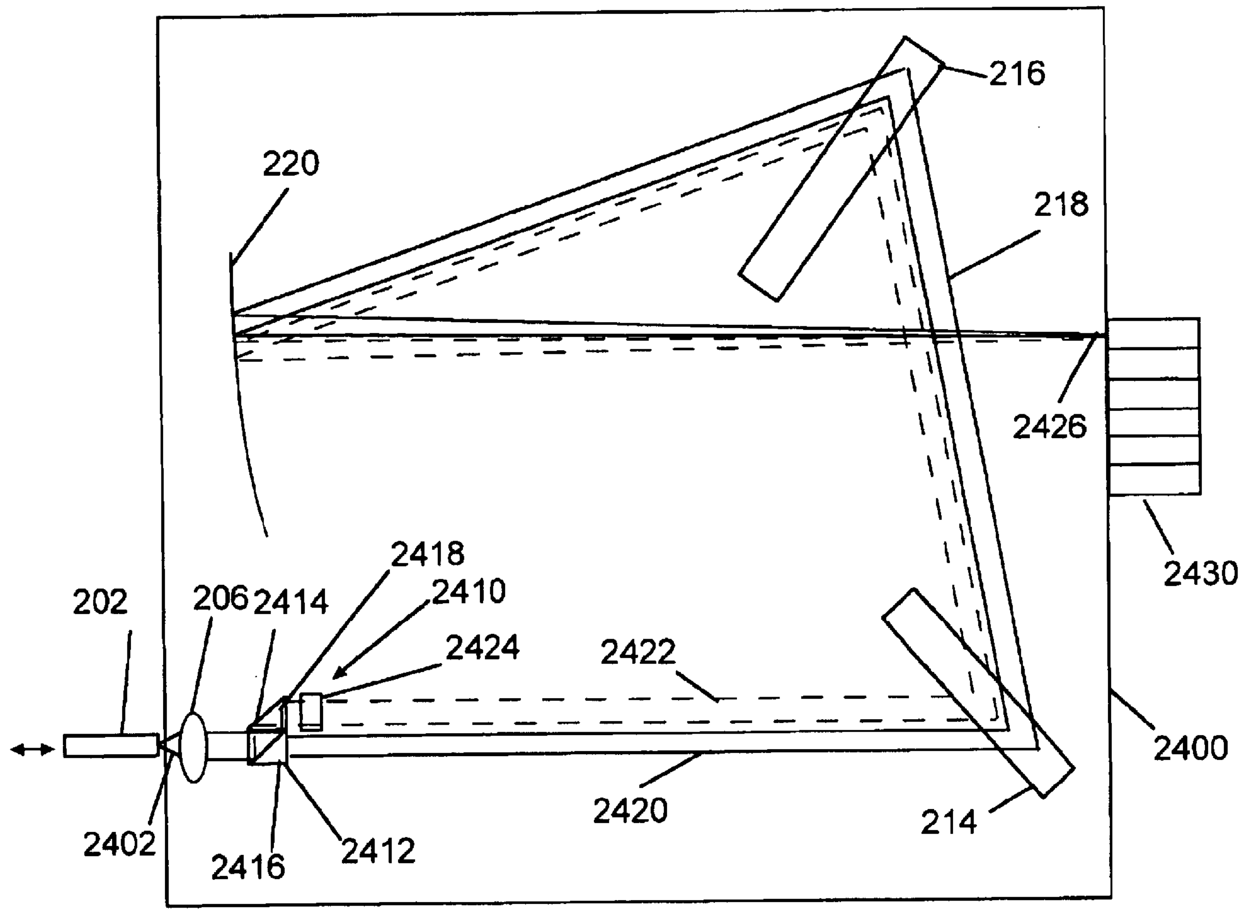

216
220
218
2426
2430
2418
2410
202
206
2414
2424
2422
2400
2420
214
2402
2416
2412

FIG. 24

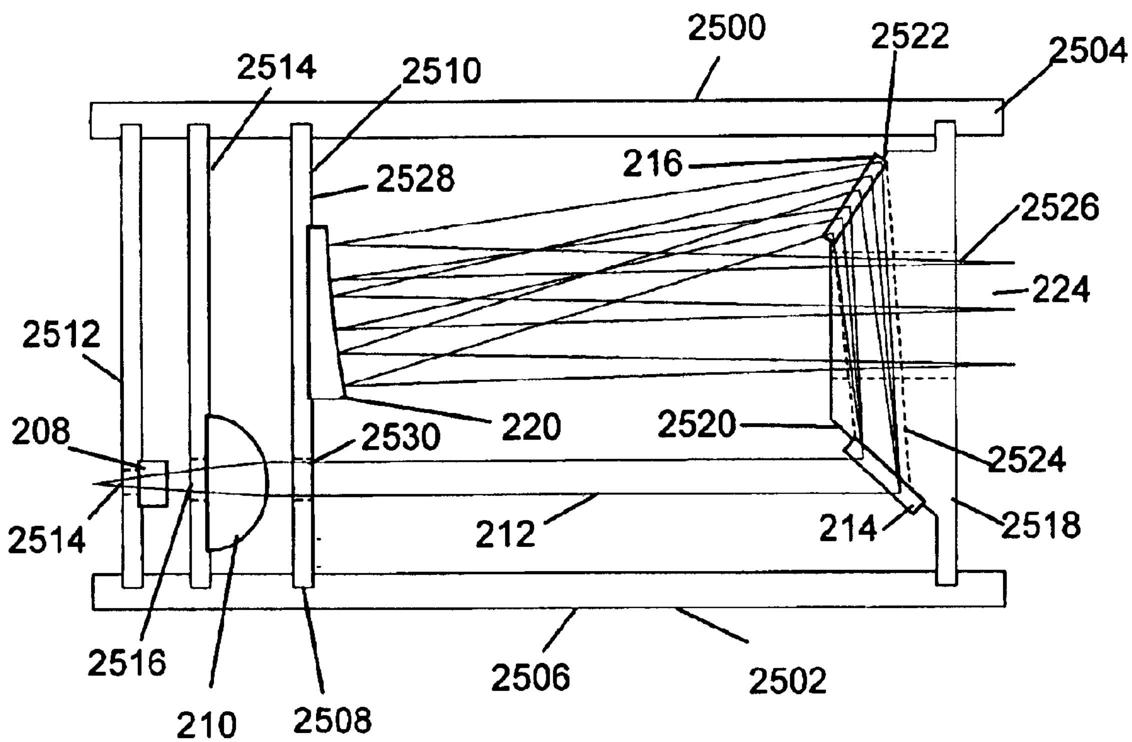


FIG. 25A

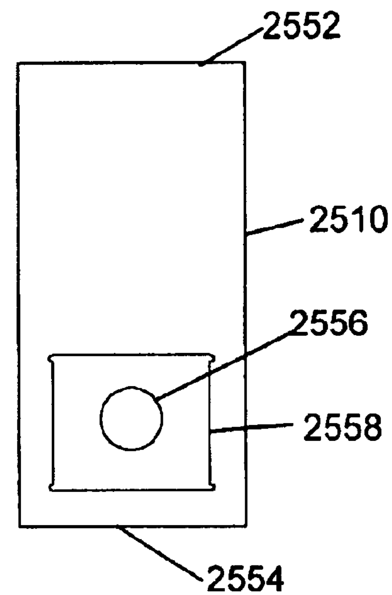


FIG. 25B

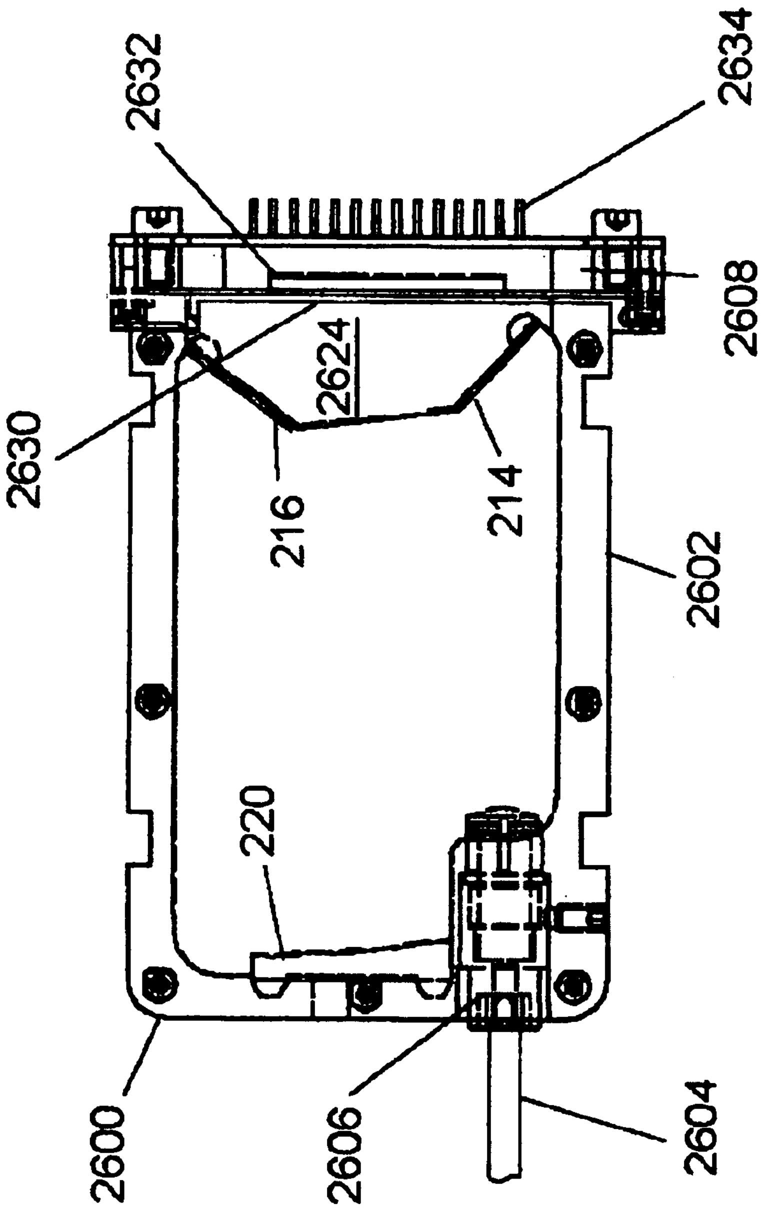


FIG. 26

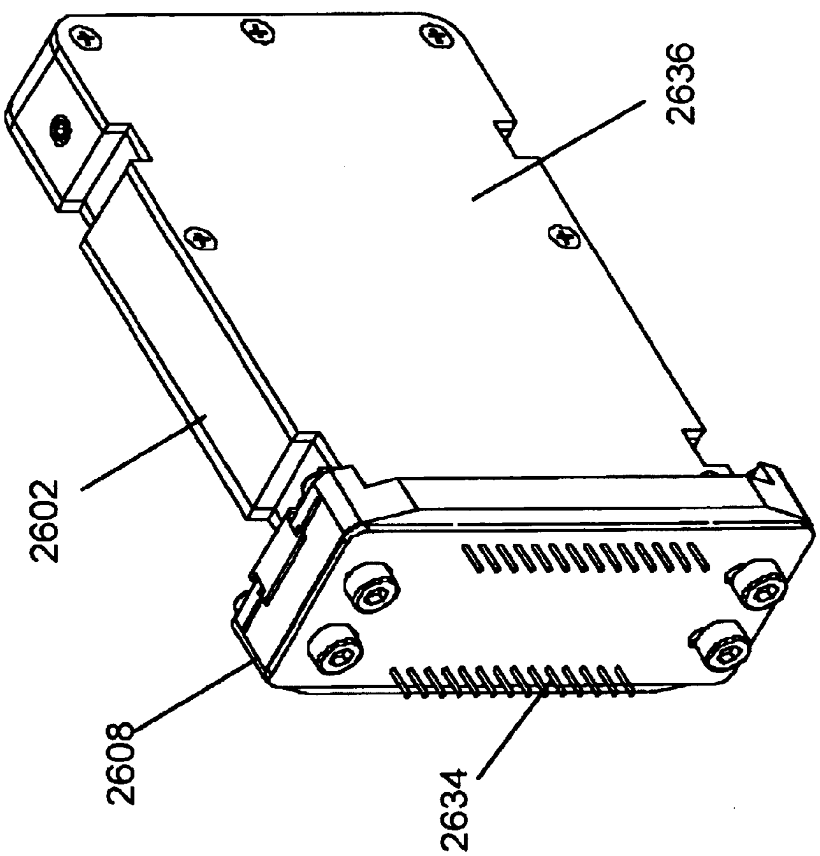


FIG. 27

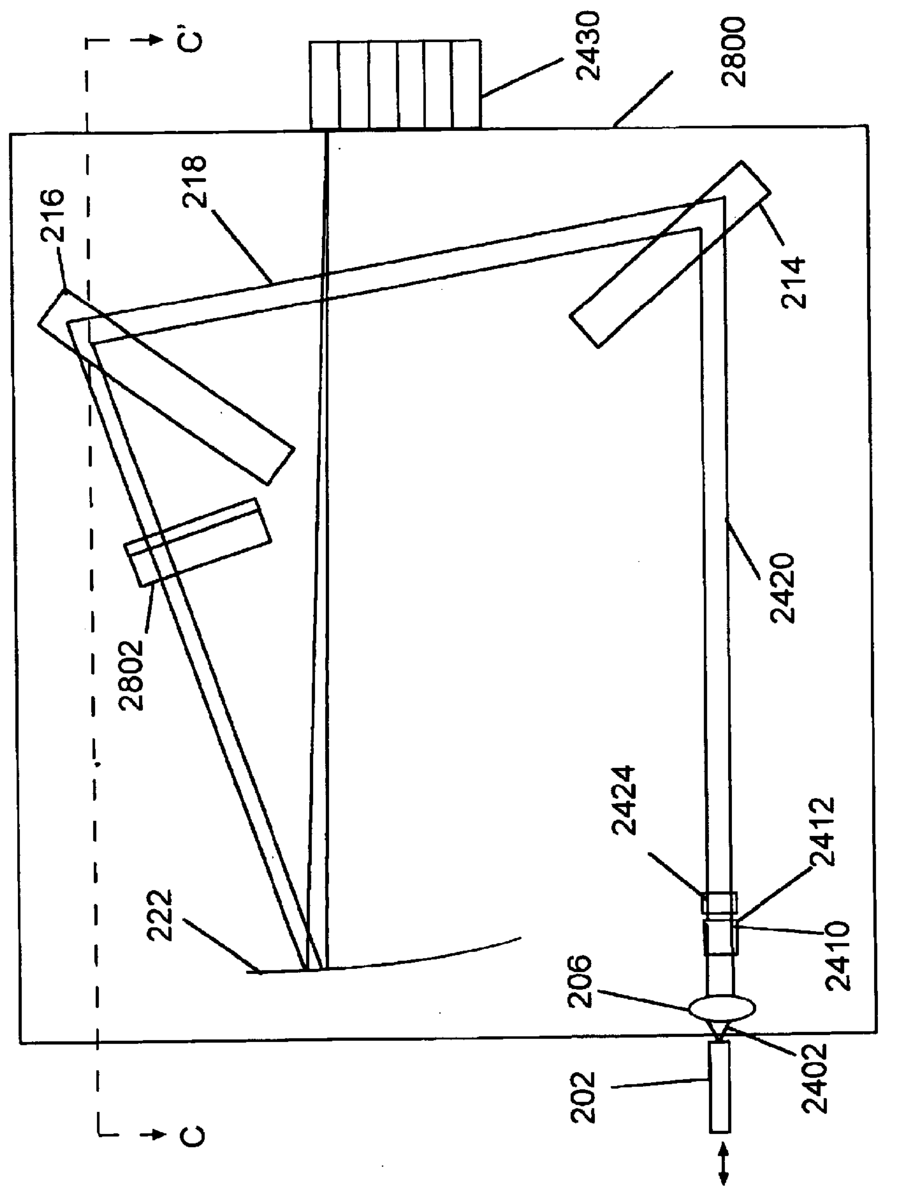

C'
2430
2800
216
218
214
2420
2802
2424
2412
2410
222
206
2402
202
C

FIG. 28

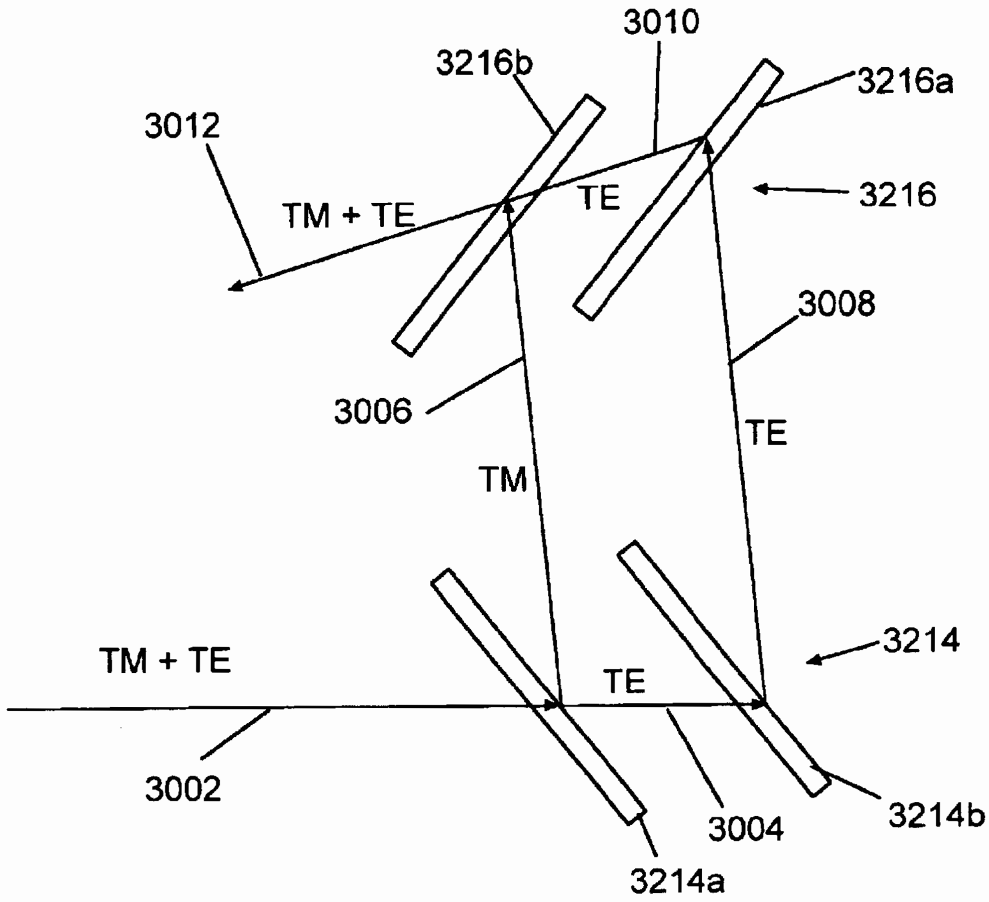

3010
3216b
3216a
3012
TE
3216
TM + TE
3008
3006
TE
TM
3214
TM + TE
TE
3002
3004
3214b
3214a

FIG. 30

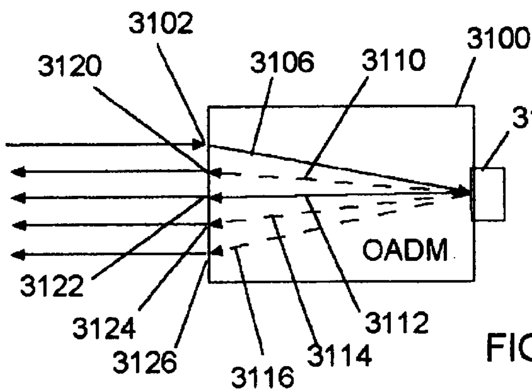


FIG. 31

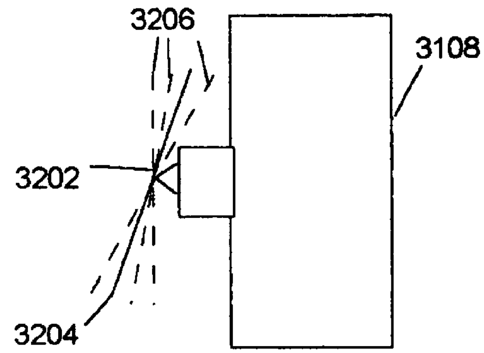


FIG. 32

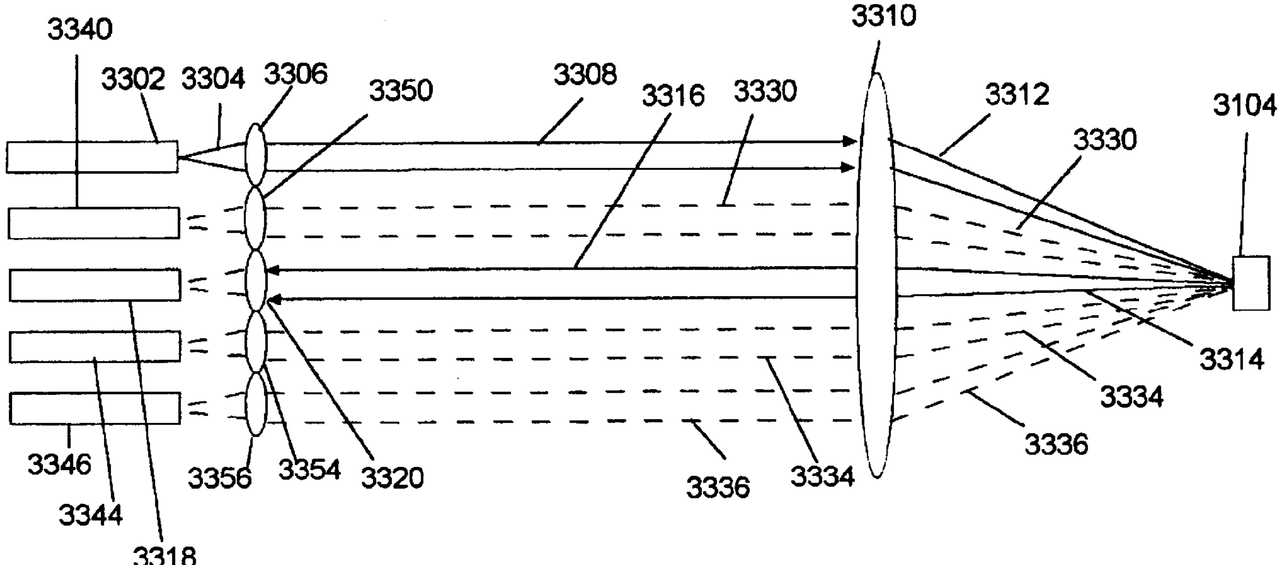


FIG. 33

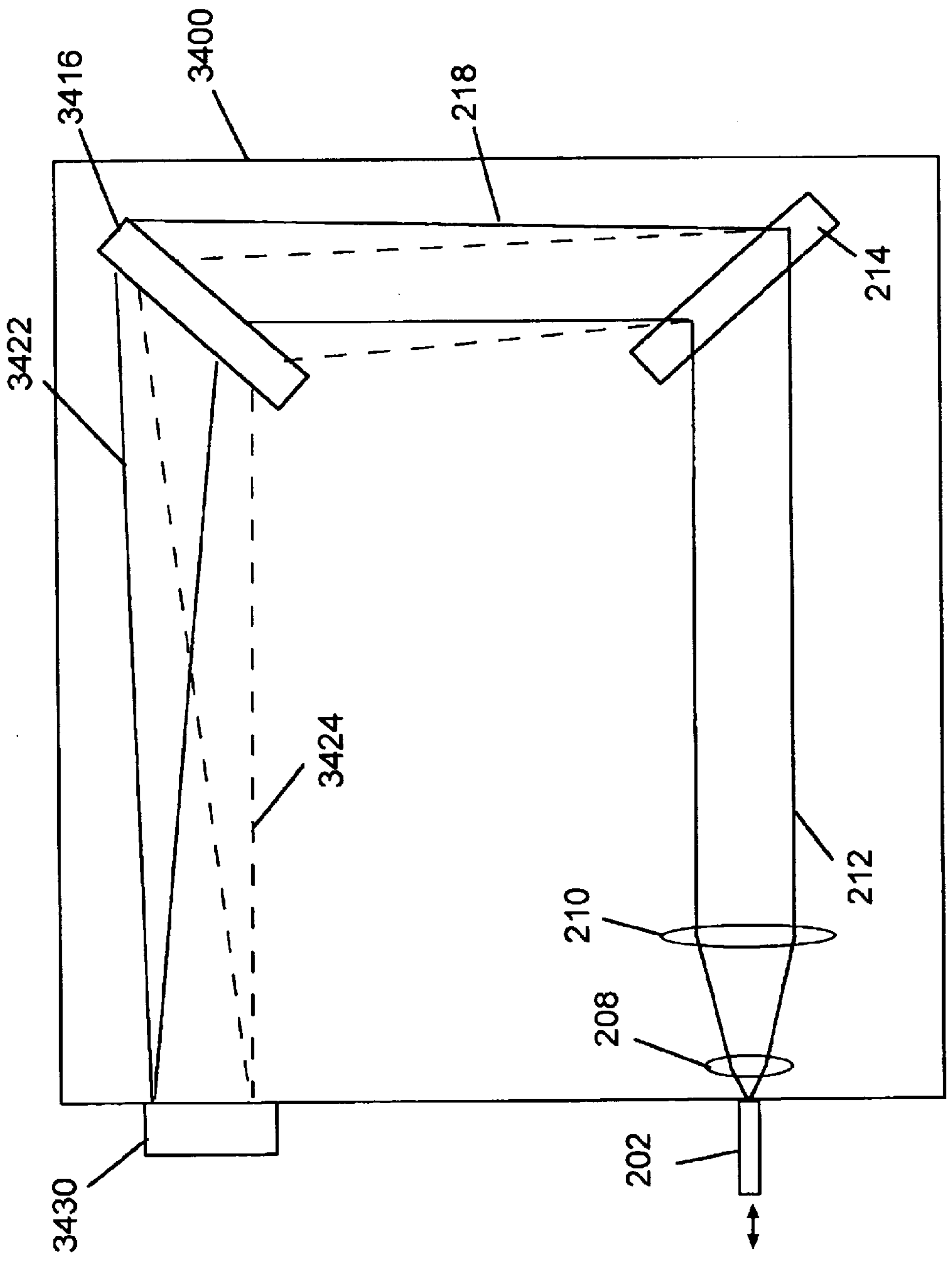


FIG. 34

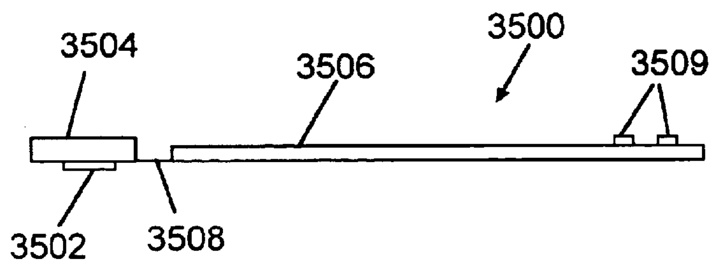


FIG. 35A

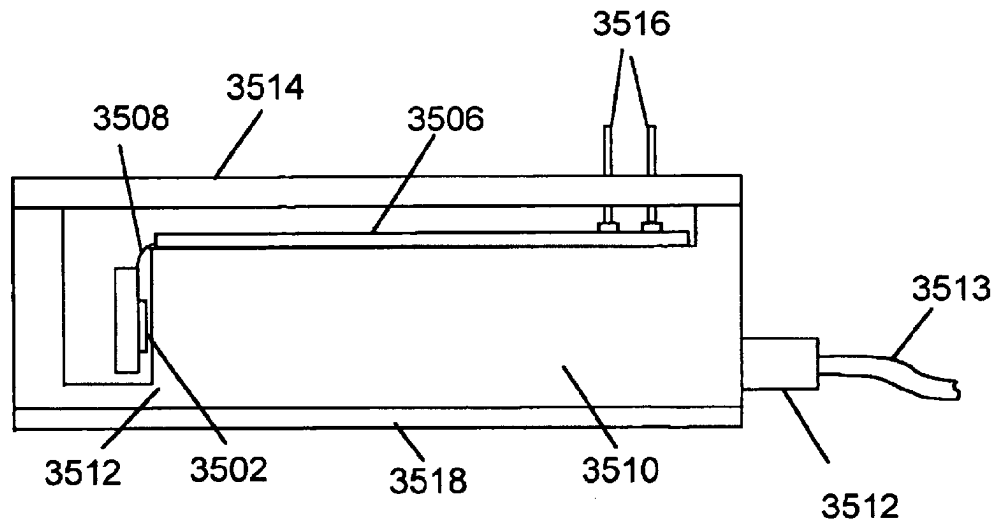


FIG. 35B

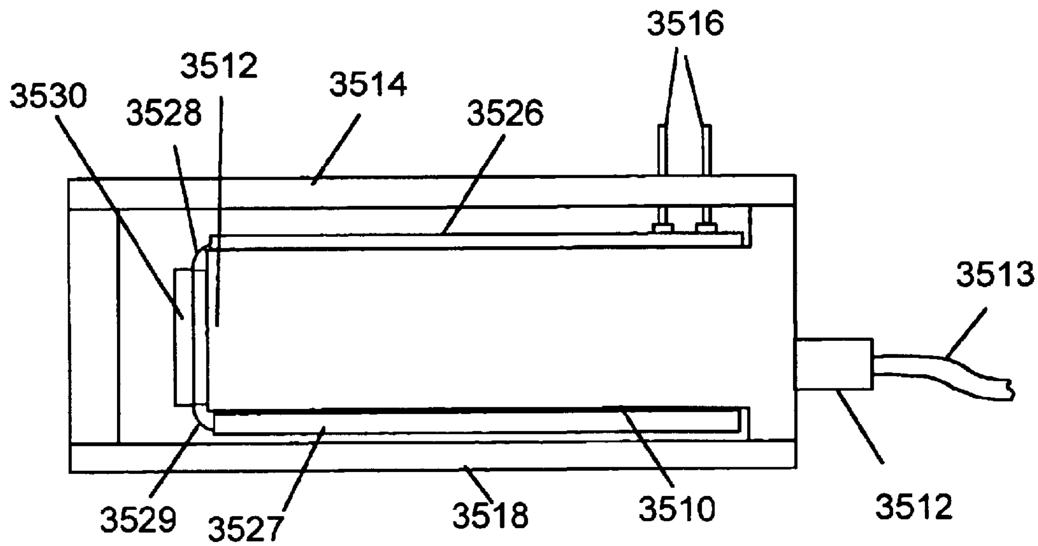


FIG. 35C

WAVELENGTH DIVISION MULTIPLEXED DEVICE

FIELD OF THE INVENTION

The present invention is directed to a device for use with multiple channel optical communications, and more particularly to a device that is useful for multiplexing/demultiplexing, channel monitoring and add/drop filtering.

BACKGROUND

One of the advantages of optical fiber communication is the potential for large information handling capacity. One approach to increasing the optical bandwidth over which information is transmitted in an optical fiber is to use wavelength division multiplexing (WDM) or dense wavelength division multiplexing (DWDM), where light at several different wavelengths is combined and injected into a fiber, the light at each wavelength typically being independently modulated with information prior to combining with the other wavelengths. After propagation through the fiber, the light is then separated into its different wavelength components before detection.

As used herein, the term WDM includes DWDM. The International Telecommunications Union (ITU) has set different WDM standards, that specify the operating wavelengths for the different WDM components, also known as channels. Under these standards, the separation between adjacent WDM channels is typically a fixed frequency. For example the inter-channel spacing may be 100 GHz or 50 GHz.

More information may be transmitted over a fixed bandwidth when the channel separation is smaller, since more channels can fit into the fixed bandwidth. However, it becomes increasingly difficult to multiplex or demultiplex the WDM channels when the frequency separation is smaller. As the pressure for increased fiber information capacity increases, the requirements for that optical WDM components can handle increasing dense multiplexing also increases.

The transmission of a multiple channel signal along a fiber link often introduces wavelength dependent losses or gains, resulting in nonuniform channel power. It is important to be able to monitor the power in different channels using a channel monitor.

Furthermore, a complex communications network typically does not consist only of point to point links, but includes one or more local loops branching off main trunk fibers. Such local loops permit smaller communities to be attached to the communications network while the trunk fiber passes between major cities. The trunk fiber includes add/drop multiplexers that select one or more channels propagating along the trunk fiber and that add channels to the trunk fiber. Several approaches to add/drop multiplexing are fixed, and permit no change in the selected channel.

SUMMARY OF THE INVENTION

Generally, the present invention relates to a WDM device that is based on the use of at least two transmissive diffraction elements. The WDM device provides flexible use and may be widely applied in WDM systems. The device is useful for multiplexing and demultiplexing, channel monitoring, and for adding and dropping channels. The device provides programmability in use as an add/drop multiplexer.

In one particular embodiment, the invention is direction to a wavelength division multiplexing device that has a first multiple channel port and a plurality of single channel ports. A diffraction unit is disposed between the first multiple channel port and the plurality of single channel ports. The diffraction unit includes at least first and second transmissive diffraction elements, and defines wavelength-specific optical paths between the first multiple channel port and respective single channel ports of the plurality of single channel ports.

Another embodiment of the invention is directed to an optical communications system that includes an optical transmitter, the optical transmitter transmitting a multiple channel communications signal; an optical receiver to detect optical signals carried in multiple optical channels; and a fiber-optic communications link coupled to transport the multiple channel communications signal from the optical transmitter to the optical receiver. One of the optical transmitter, the optical receiver and the fiber-optic communications link includes a multiple wavelength device. The multiple wavelength device has a first multiple channel port and a plurality of single channel ports. The diffraction unit includes at least first and second transmissive diffraction elements, and defines wavelength-specific optical paths between the first multiple channel port and respective single channel ports of the plurality of single channel ports.

Another embodiment of the invention is directed to a method of analyzing a multiple channel communications signal. The method includes diffracting the multiple channel communications signal with a first transmission diffraction element, and diffracting light from the first transmission diffracting element with a second transmission diffraction element. The method also includes focusing light from the second transmission diffraction element so as to separate individual channel beams at respective single channel ports.

Another embodiment of the invention is directed to a system for analyzing a multiple channel communications signal. The system includes means for diffracting the multiple channel communications signal with a first transmission diffraction element and means for diffracting light from the first transmission diffracting element with a second transmission diffraction element. The system also includes means for focusing light from the second transmission diffraction element so as to separate individual channel beams at respective single channel ports.

Another embodiment of the invention is directed to a method of combining communications channels to produce a multiple communications signal. The method includes diffracting at least first and second communications channel beams with a first transmission diffraction element diffracting the first and second communication channel beams with at least a second transmission diffraction element so that the at least first and second communications channel beams are spatially overlapped and propagating along a common direction.

Another embodiment of the invention is directed to a device for combining communications channels to produce a multiple communications signal analyzing a multiple channel communications signal. The device includes means for diffracting at least first and second communications channel beams with a first transmission diffraction element; and means for diffracting the first and second communication channel beams with a second transmission diffraction element so that the at least first and second communications channel beams are spatially overlapped and propagating along a common direction.

Another embodiment of the invention is directed to an optical system that includes a frame having first and second

members. The first member has a plurality of first slots across a first face opposing the second member, and the second member has a plurality of corresponding second slots across a second face opposing the first member. The system also includes a plurality of plates, a first side of each plate being positioned in a first slot and a second side of each plate being positioned in the second slot corresponding to the respective first slot. Optical elements are mounted on the plurality of plates in positions to form an optical path in the optical system.

Another embodiment of the invention is directed to a method of assembling an optical system. The method includes mounting optical elements on respective plates having first and second opposing edges and mounting each plate in corresponding slots on first and second members of a frame so as to passively align the optical elements, thus forming the optical system.

The above summary of the present invention is not intended to describe each illustrated embodiment or every implementation of the present invention. The figures and the detailed description which follow more particularly exemplify these embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention may be more completely understood in consideration of the following detailed description of various embodiments of the invention in connection with the accompanying drawings, in which:

FIG. **1** schematically illustrates a fiber optical communications network;

FIG. **2** schematically illustrates a double transmission grating multiplexer according to an embodiment of the present invention;

FIG. **3** is a schematic cross-sectional view of one embodiment of a transmission grating, according to the invention;

FIG. **4** is a schematic cross-sectional view of a second embodiment of a transmission grating, according to the invention;

FIG. **5** is a schematic cross-sectional view of a third embodiment of a transmission grating, according to the invention;

FIG. **6** schematically illustrates a double transmission grating channel monitor according to an embodiment of the present invention;

FIG. **7** schematically illustrates a system for controlling spectral flatness in a DWDM signal using the channel monitor illustrated in FIG. **6**;

FIG. **8** schematically illustrates a double transmission grating optical add/drop multiplexer according an embodiment of the present invention;

FIGS. **9**A and **9**B schematically illustrate a MEMS transmission switch in reflective and transmissive states respectively;

FIG. **10** illustrates the add/drop multiplexer of FIG. **8** connected to a fiber network;

FIG. **11** schematically illustrates a reflective add/drop multiplexer of the present invention connected to a fiber network;

FIGS. **12**A and **12**B schematically illustrate optical paths within a reflective add/drop multiplexer of an embodiment of the present invention with a switch in first and second activation states respectively;

FIG. **13** schematically illustrates input and output coupling optics of an embodiment of a reflective add/drop multiplexer of the present invention;

FIGS. **14**A and **14**B schematically illustrate an embodiment of a MEMS reflection switch in first and second activation states respectively;

FIGS. **15**A and **15**B schematically illustrate optical paths within a reflective add/drop multiplexer of another embodiment of the present invention, with a switch in first and second activation states respectively;

FIG. **16** schematically illustrates input and output coupling optics of another embodiment of a reflective add/drop multiplexer of the present invention;

FIGS. **17**A and **17**B schematically illustrate another embodiment of a MEMS reflection switch in first and second activation states respectively;

FIGS. **18**A and **18**B schematically illustrate equivalent optical paths through embodiments of a reflective add/drop multiplexer according to the present invention, having common and separate focusing elements respectively;

FIG. **19** shows a plot comparing dispersions in the light dispersed region using spherical and aspherical focusing components; and

FIG. **20** illustrates an embodiment of the invention using aspherical focusing components;

FIG. **21** schematically illustrates a double transmission grating device according to the present invention that uses a transmissive focusing system for focusing light from the transmission gratings to the light dispersion region;

FIG. **22** schematically illustrates an embodiment of a transmission grating device that has two output ports, according to the present invention;

FIG. **23** schematically illustrates a double transmission grating device that has three transmission gratings, according to the present invention;

FIG. **24** schematically illustrates an embodiment of a double transmission grating device that includes a polarization separator according to the present invention;

FIGS. **25**A and **25**B schematically illustrate an embodiment of a mechanical frame for assembling a double transmission grating device according to the present invention;

FIGS. **26** and **27** schematically illustrate another embodiment of a mechanical frame for assembling a double transmission grating device according to the present invention;

FIG. **28** schematically illustrates another embodiment of a double transmission grating device that includes a polarization separator according to the present invention;

FIG. **29** schematically illustrates cross-section CC' of the device illustrated in FIG. **28**;

FIG. **30** schematically illustrates an embodiment of dual transmission diffraction gratings that provide high diffraction efficiency to randomly polarized light;

FIG. **31** schematically illustrates an embodiment of a device according to the present invention having multiple input and output ports;

FIG. **32** illustrates a multiple position optical switch for use with the embodiment of device illustrated in FIG. **31**;

FIG. **33** schematically illustrates equivalent optical paths through the device illustrated in FIG. **31**;

FIG. **34** schematically illustrates an embodiment of the present invention that uses a diffractive optical element for focusing light as well as dispersing light; and

FIGS. **35**A–**35**C schematically illustrate approaches to mounting an electronic circuit in the embodiment illustrated in FIGS. **26** and **27** according to the present invention.

While the invention is amenable to various modifications and alternative forms, specifics thereof have been shown by

way of example in the drawings and will be described in detail. It should be understood, however, that the intention is not to limit the invention to the particular embodiments described. On the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION

The present invention is applicable to transmission grating spectrometers, and is believed to be particularly useful in dense wavelength division multiplexed (DWDM) applications for optical communications.

DWDM communications systems use several channels of light at different optical frequencies. According to the ITU standards, the channels are evenly spaced by frequency. Thus, the mth channel has a frequency given by $\nu_o+m\Delta\nu$, where ν_o is a lowest channel frequency, $\Delta\nu$ is the channel separation and m is an integer value ranging from 0 to m_0, the upper value. The value of m_0 may be any suitable number, for example 19, 39, 79, or higher. According to commonly used ITU standards, the channel separation, $\Delta\nu$, may be, amongst other values, 100 GHz or 50 GHz. In the following discussion, the different DWDM channels are described in terms of both frequency and wavelength. It will be appreciated that each channel has a unique wavelength and frequency given through the relationship $\nu_m.\lambda_m=c$, where ν_m and λ_m are, respectively, the frequency and wavelength of the mth channel, and c is the speed of light.

One particular embodiment of a DWDM optical communications system **100** is illustrated in schematic form in FIG. **1**. A DWDM transmitter **102** directs a DWDM signal having m_0 channels through a fiber communications link **104** to a DWDM receiver **106**.

This particular embodiment of DWDM transmitter **102** includes a number of light sources **108***a*–**108***m* that generate light at different wavelengths, **λ0**, **λ1** . . . λm_0, corresponding to the different optical channels. The light output from the light sources **108***a*–**108***m* is combined in a DWDM combiner unit **110**, or multiplexer (MUX) unit to produce a DWDM output **112** propagating along the fiber link **104**.

Light sources **108***a*–**108***m* may be modulated laser sources, or laser sources whose output is externally modulated, or the like. It will be appreciated that the DWDM transmitter **102** may be configured in many different ways to produce the DWDM output **112**. For example, the MUX unit **110** may include an interleaver to interleave the outputs from different multiplexers. Furthermore, the DWDM transmitter **102** may be equipped with any suitable number of light sources for generating the required number of optical channels. For example, there may be twenty, forty or eighty optical channels, or more. The DWDM transmitter **102** may also be redundantly equipped with additional light sources to replace failed light sources.

Upon reaching the DWDM receiver 106, the DWDM signal is passed through a demultiplexer unit (DMUX) **130**, which separates the multiplexed signal into individual channels that are directed to respective detectors **132***a*–**132***m*.

The fiber link **104** may include one or more fiber amplifier units **114**, for example rare earth-doped fiber amplifiers, Raman fiber amplifiers or a combination of rare earth-doped and Raman fiber amplifiers. The fiber link **104** may include one or more DWDM channel monitors **126** for monitoring the power in each of the channels propagating along the link **104**. Typically, a fraction of the light propagating along the fiber link **104** is coupled out by a coupler **124** and directed to the DWDM channel monitor **126**.

The fiber link **104** may include one or more optical add/drop multiplexers (OADM) **116** for directing one or more channels to a local loop. In the particular embodiment illustrated, the OADM **116** drops the ith channel, operating at wavelength λi, and directs it to the local loop **118**. The local loop **118** also directs information back to the OADM **116** for propagating along the fiber link **104** to the DWDM receiver **106**. In the illustrated embodiment, the information added at the OADM **116** from the local loop **116** is contained in the ith channel at λi. It will be appreciated that the information directed from the local loop **118** to the OADM **116** need not be at the same wavelength as the information directed to the local loop **118** from the OADM **116**. Furthermore, it will be appreciated that the OADM **116** may direct more than one channel to, and may receive more than one channel from, the local loop **118**.

The fiber link **104** may also include one or more optical cross-connect switches **134**, for connecting to other optical circuits. The WDM signal from the transmitter unit **102** is typically demultiplexed in a DMUX **130** and the demultiplexed signal is then fed into the optical cross-connect switch array **134**, which couples signals from the DMUX **130** and from other systems through ports **136**. On the output side of the optical cross-connect switch array **134**, some output signals are coupled to a MUX **132** that multiplexes the output signals into a WDM signal that is transmitted to the receiver unit **106**. Other outputs **138** from the optical cross-connect switch array **134** may be coupled to other systems.

An embodiment of a double transmission diffraction grating-based WDM device **200** that is useful in DWDM communications is illustrated in FIG. **2**. In this particular embodiment, light is typically fed into the device **200** via a waveguide **202**, for example an optical fiber, that carries a WDM light signal. The multiple channel light **204** from the fiber **202** is collimated by a collimating/focusing system **206**, that may comprise one or more lenses. In the particular embodiment illustrated, the lens system **206** includes a first lens **208** and a second lens **210**. The first and second lenses **208** may be cylindrical lenses, spherical lenses or aspherical lenses, or any other suitable type of focusing element.

The collimated light beam **212** is incident on a first transmission diffraction grating **214**. The transmission diffraction grating **214** may be formed from glass, and other suitable materials that transmit light at the wavelength range of interest. Such materials may include Si, SiO_2, Si_3N_4 and SiON. One applicable wavelength range of interest is 800 nm–2000 nm, which covers the range of wavelengths typically selected for optical fiber communications, although it will be appreciated that other wavelength ranges may be used.

The term transmission diffraction grating as used herein refers to structures that diffract light passing therethrough. The transmission diffraction grating may have a strictly periodic structure, known as a linear grating, or may have a structure that is not strictly periodic, termed a nonlinear grating. For example, the structure may have a chirped period, where the period changes from one end of the structure to the other. Use of a chirped grating requires the use of a different focusing element from a linear grating. If there is a substantial variation in the periodicity of the transmission diffraction grating, then the transmission diffraction grating demonstrates focusing capabilities in addition to dispersing the different wavelengths of the light passing therethrough. Such a grating may also be termed a diffractive optical element (DOE). In the following description, the terms transmission diffraction grating refers

to both linear and nonlinear gratings. Many of the examples described below illustrate the use of a linear grating, but it will be appreciated by those of ordinary skill in the art that nonlinear transmission gratings may also be used.

One approach to forming a transmission diffraction grating **214** is to etch a slotted structure into a substrate. The depth and length of the slots, and the ratio of the etched slot width to the unetched material width between slots, determine, at least in part, the diffraction properties of the transmission diffraction grating **214**. The spatial variation in grating periodicity determines the focusing capabilities of the transmission diffraction grating **214**. The transmission diffraction grating **214** may have a diffraction efficiency into the first diffraction order as high as 99.9%. In one embodiment of a grating **214**, particularly suitable where the light entering the device **200** is TE polarized, the grating is formed from fused silica, the grating period is 1050 nm, with a groove duty cycle of 51%. The groove depth is about 2 μm and the incident angle on the grating is about 31°. In another embodiment of grating, particularly suitable for randomly polarized light, the groove depth is about 6.7 μm.

The collimated light beam **212** is diffracted by the first transmission diffraction grating **214** towards a second transmission diffraction grating **216** as a singly-diffracted beam **218**. The singly-diffracted beam **218** is diffracted by the second transmission diffraction grating **216** towards a focusing optic **220** as a doubly-diffracted beam **222**. The first and second transmission gratings **214** and **216** are typically oriented so as to diffract light into the first diffraction order.

Transmission diffraction gratings have advantages over reflection diffraction gratings. For example, the use of a transmission grating provides the designer with more design parameters to adjust in order to obtain optimum operation. The characteristics of a reflection grating are determined by the geometrical shape of the grating. In contrast, the material of the transmission grating may also be used as a design parameter. Another benefit to using a transmission grating is that it may be designed to have a high diffraction efficiency over a broader wavelength range than is typically possible using a reflection grating. In addition, the use of two gratings rather than a single grating is that, where the grating period is constant, the dispersion is increased, and so effective channel separation may be achieved in a smaller device than a single grating device.

The focusing optic **220** directs and focuses the doubly diffracted beam **222** towards a light dispersed region **224**. The doubly-diffracted beam **222** includes components **226** of different wavelength, corresponding to different optical channels, that propagate along different paths due to diffraction at the first and second transmission diffraction gratings **214** and **216**. By focusing the different wavelength components **226** at the light dispersed region **224**, the different wavelength components **226** are physically separated and may subsequently be operated on individually and separately from the other wavelength components **226** by a light handling unit **230**. The focusing optic **220** may be a spherical or an aspherical mirror. An aspherical mirror may permit the different channels to be focused at the light dispersed region **224** with uniform spacing, as is discussed further below.

In the illustrated embodiment, the light handling unit **230** is an array **228** of single channel waveguides **232**, such as optical fibers. The separation between the cores of adjacent optical fibers **232** may be set to be the same as the spatial separation of the individual channels at the light dispersed region **224**. Thus, individual channels may be matched to respective fibers **232**. Where aspheric focusing optics are used, the separation between fibers **232** may be uniform. However, the separation between fibers **232** need not be uniform, and may be set to match the dispersion of the different channels at the light dispersed region. A lens array **234** may be positioned so that the individual lenses of the lens array focus each channel into its respective fiber **232**. An advantage provided by the lens array is an increase in coupling efficiency into the fibers **232**. The spacing of the lenses on the lens array is typically arranged to match the spacing of the fibers **232**. Therefore, if the fibers **232** are uniformly spaced, the lenses of the lens array **234** are typically uniformly spaced. On the other hand, if the fiber spacing is nonuniform, then the lens spacing is typically nonuniform in a manner that matches the nonuniformity in the fiber spacing.

Therefore, where a multiple channel signal propagates into the device **200** through fiber **202**, light of individual channels propagates away from the device along individual fibers **232**. It will be appreciated that in such a configuration, the device **200** operates as a demultiplexer (DMUX).

It will be appreciated that, if single channel light is directed along the fibers **232** towards the device **200**, then the light at the different channels may be combined by the transmission diffraction gratings **216** and **214** to produce a multiple channel output signal at the fiber **202**. In such a configuration, the device **200** operates as a multiplexer (MUX).

It will also be appreciated that the device **200** may accommodate a large number of optical channels, with a requisite number of fibers in the fiber array **228**, and is not restricted to using only six channels into six fibers as illustrated in the figure.

An example of a transmission grating **300** suitable for use in the device **200** is illustrated in FIG. **3**. The transmission grating **300** includes a substrate **302** that defines a grating structure **304**. In operation, light may be incident on a non-grating surface **306** of the substrate **302** and transmitted through the substrate **302** and diffracted by the grating structure **304**. Light may also be incident on the grating structure **304** and then pass through the non-grated surface **302**. This operation contrasts with a reflection grating in which light is incident on the surface containing the grating structure and is reflectively diffracted away from that surface.

The transmission grating **300** optionally may include an antireflection coating (not shown) on the non-grated surface **306** to reduce reflection of incident light at that surface. Typically, any antireflection coating material can be used although, preferably, the antireflection coating has little or no absorption in the wavelength region of light diffracted by the transmission grating **300**.

Light incident on the transmission grating at an angle, α, from an axis perpendicular to the non-grated surface, in other words perpendicular to a normal to the grating, is typically diffracted from the grating surface according to the diffraction equation:

$$m\lambda = d(n_{in} \sin \alpha + n_{out} \sin \beta) \quad (1)$$

where m is an integer (. . . , −2, −1, 0, 1, 2, . . .) representing the diffraction order, λ is the wavelength of the incident light, d is the period of the grating, and β is the angle from the grating normal at which the light is diffracted. The refractive indices n_{in} and n_{out} are the refractive indices of the input medium and output medium respectively. Where the transmission grating **300** is used in air, then $n_{in}=n_{out}=1$. The separation of light at different wavelengths by the transmis-

sion grating **300** is also termed dispersion. Where d is constant across the substrate, the grating is a linear grating. The period, d, may have a functional dependence on spatial position on the substrate, in which case the grating is termed a nonlinear grating. Only a linear grating is illustrated in FIGS. **3–5**, but it will be appreciated that nonlinear gratings may also be used.

By proper choice of incident light angle according to equation (1), several monochromatic light beams, for example different optical channels, may be combined into a polychromatic light beam using the transmission grating. In such an operation, the incident angles, α_1, α_2, . . . , are selected so that β is approximately the same for each channel.

Any suitable grating profile may be used, including, for example, triangular, square or rectangular well (shown in FIG. **3**), blazed, and sinusoidal grating structures. The structural parameters of the grating structure may be selected to obtain the desired diffraction properties. The structural parameters include i) the grating period, in other words the average center-to-center inter-well spacing, which is convertible to the number of grating lines per mm; ii) the aspect ratio, in other words, the well width divided by the well depth; iii) the duty cycle, in other words the width of the tooth (between wells) divided by the grating period; iv) the angle of blazing for blazed gratings, and v) grating chirp, the variation of period along the length of the grating. The embodiment of grating **300** illustrated in FIG. **3** has a duty cycle of 50%. In addition, spatial variations in the periodicity across the substrate may give rise to focusing effects.

In some embodiments, the parameters of the grating are selected to result in at least 50%, 75%, or 90% or more of the incident light being diffracted into a single diffraction order. The diffraction of light into a single diffraction order or a small number of diffraction orders may be modeled using a commercial grating design modeling program, such as Gsolver, available from Grating Solver Development Company, Texas. The design of the grating is typically optimized for high, uniform diffraction efficiency over the bandwidth of interest, for example the erbium C-band, L-band or both. Maximum diffraction efficiency is typically set for the center wavelength of the desired band.

In addition, in some embodiments, the structural parameters of the grating may be selected so that the diffraction efficiency for the TE and TM polarization states of the incident light is within no more that 10% or 5%. Other examples of transmission diffraction gratings are described in U.S. patent application Ser. No. 09/789,888, entitled "Grating structures and Methods of Making the Grating Structures",filed on Feb. 21, 2001 and naming J. Holm, H. Madsen, S. Weichel, P. E. Isben and B. Rose as inventors, and incorporated herein by reference.

The substrate used to form the transmission grating is typically formed using a material that is transparent to the wavelengths of light to be diffracted. The absorption in the transmission grating **300** is typically less than 5% and preferably less than 1%. Suitable materials for diffraction of light in the 1.3 μm–1.6 μm wavelength range typically used for fiber optical communications include, for example, quartz, silicon, and silicon nitride. Other suitable materials include, for example, plastics and other materials suited for replication.

The grating structure may be formed using a variety of different techniques. One technique includes mechanical ruling using a stylus or other ruling device having a hard tip, such as diamond or silicon carbide. Other techniques include the use of photolithographic methods, such as standard lithography, those using a holographic mask, near-field holography and direct holographic exposure to form a grating pattern in a photoresist material deposited on the substrate. The substrate can then be etched according to the grating pattern using any wet or dry etching techniques to form the grating. Appropriate wet and dry etching techniques and etchants typically depend on the material used for the substrate. Some examples of photoilthographic methods suitable for forming a diffraction grating are discussed in U.S. patent application Ser. No. 09/789,888, entitled "Grating structures and Methods of Making the Grating Structures",filed on Feb. 21, 2001 and naming J. Holm, H. Madsen, S. Weichel, P. E. Isben and B. Rose as inventors.

Another example of a suitable transmission grating **400** is illustrated in FIG. **4**. This transmission grating **400** includes a grating structure **404** disposed internally within a substrate **402**. In one embodiment, the substrate **402** includes a first piece **408**, containing the grating structure **404** formed on a surface, and a second piece **410**. The first and second pieces **408, 410** can by combined together to form the substrate **402** using a variety of techniques. For example, the first and second pieces **408, 410** may be bonded or adhesively coupled using an optical adhesive; the two pieces **408** and **410** may be reactively bonded using reactive groups on the surface of the two pieces that are, optionally, photochemically or thermally activated; or the two pieces can be mechanically coupled using a clamp or other fastener to hold the pieces together. Methods of bonding or otherwise attaching the first and second pieces **408** and **410** are discussed in U.S. patent application Ser. No. 09/789,888, entitled "Grating structures and Methods of Making the Grating Structures", filed on Feb. 21, 2001 and naming J. Holm, H. Madsen, S. Weichel, P. E. Isben and B. Rose as inventors. The two pieces **408** and **410** may also be assembled by optically contacting polished surfaces. As another example, the second piece **410** may be formed by deposition of material over and, optionally, within the grating structure. Suitable deposition techniques include, for example, chemical vapor deposition (CVD), physical vapor deposition, sputtering, and the like.

In some embodiments of the structure illustrated in FIG. **4**, the material used for the first and second pieces **408, 410** of the substrate **402** is the same. In other embodiments, the materials are different.

The two pieces **408, 410** may have the same thickness or a different thickness. If the two pieces **408, 410** are made of the same material and have the same thickness, the position at which the light exits the transmission grating **400** will be substantially independent of the temperature of the grating **400**, where the light is incident on the grating at the Bragg angle. The Bragg angle is that angle of incidence which produces a diffracted beam whose output angle is equal to the angle of incidence.

In another embodiment, illustrated in FIG. **5**, the grating structure **504, 505** is formed in both of the first and second pieces **508, 510** and the two grating structures **504** and **505** are aligned to form a single grating having a depth greater than either of the two individual grating structures. This procedure may be used to form a grating having deep wells or a large aspect ratio.

One advantage of the transmission gratings of FIGS. **4** and **5** is that the grating structure is within the substrate. This prevents foreign matter from entering the grating grooves and avoids degradation of the grating due to exposure to outside elements. This approach also permits higher diffraction efficiency for a broader range of grating parameters. The two outer surfaces through which the light passes may both be antireflection coated in order to reduce loss.

The device **200** is useful for other applications, in addition to multiplexing and demultiplexing. Another particular embodiment of the device **600** is illustrated in FIG. **6**, which shows a double transmission diffraction grating device **600** that is useful for channel monitoring. Like components are numbered with the same numbers as before. A multiple channel signal is fed into the device **600** from a fiber **602**. The multiple channel signal is separated into its constituent channel components at the light dispersed region **224**.

The light handling unit **230** is a detector unit **604** disposed at the light dispersed region **224** to detect the power level in each channel. The detector unit **604** typically includes a number of individual photodetectors **606**. The photodetectors **606** may be individual photodiodes, each photodiode arranged to detect light in its respective channel and producing its own analog output. This approach is suitable for monitoring the power in each channel. The photodetectors **606** may also comprise an integrated photodetector array, for example an integrated array of photodiodes or charged coupled devices. Such an integrated array typically includes a large number of pixels, for example up to 256 pixels, or higher. The use of an integrated array not only permits power monitoring, but also permits wavelength measurement of the individual channels, and also permits the measurement of noise between the channels.

The output from the detector unit **604** is directed to a channel analysis unit **608**, that analyzes the signals from the photodetectors **606**. In the illustrated embodiment, the channel analysis unit **608** includes a display **610** showing a signal **612** such as might be generated using an integrated photodiode array. The signal **612** shows individual peaks **614** corresponding to the individual channels. The heights of the peaks **614** indicate the power level in each channel. The position across the screen **610** of each peak **614** indicates its respective wavelength. The regions **616** between the peaks show whether there is any interchannel noise.

The device **600** may be used as a channel monitor for monitoring the power levels in each channel. This is useful for monitoring gain equalization in fiber amplifiers, fault detection in optical add/drop multiplexers (OADMs), and power equalization near transmitters and/or OADMs.

The device **600** may be provided with a focusing/collimating unit **620** that provides spatial filtering to the light entering the device **600** from the fiber **602**. In the particular embodiment illustrated, the focusing/collimating unit **620** includes a first lens **628** for focusing the light for the fiber **602** through an aperture plate **622** to a collimating lens **630**. The collimating lens **630** collimates the light to produce the collimated beam **212**. It will be appreciated that other configurations of spatial filters may be used in the focusing/collimating unit **620**. An advantage of using a spatial filter is that it reduces the possibility of stray light entering the monitor device, and thus enhances the signal to noise ratio of detection signals produced by the detector unit **604**.

It will be appreciated that a spatial filter may be provided in the other embodiments of device discussed herein, and that light may pass through the spatial filter in both directions. Thus, a spatial filter may also be provided to an input to a MUX/DMUX or add/drop multiplexer device.

One particular application for a channel monitor **700** is illustrated in FIG. **7**. A fiber **702** includes a fiber amplifier **704**, such as an erbium-doped fiber amplifier or a Raman fiber amplifier. Pump light is generated by one or more pump lasers **706** and is coupled into the fiber **702** via a coupler **708**. A portion of the amplified signal is coupled out of the fiber **702** by the coupler **710** and directed to the channel monitor **700**. The channel monitor **700** detects the power levels of the individual channels propagating along the fiber. The process of amplification in the amplifier **704** may favor some channels over others, with the result that the favored channels have power levels greater than the power levels of other channels. It is often preferred that the power levels of the different channels be uniform, in order to keep the power spread among the channels within the receivers' dynamic range.

The channel monitor **700** feeds a monitor signal to the analyzer/control unit **712**, which analyzes the monitor signal. The analyzer/control unit **712** may then change the wavelength or pump power of one or more of the pump lasers **706** in order to change the net gain profile for the amplifier **704**, in order to make the individual channel powers more uniform. The analyzer/control unit **712** may also adjust the losses in a programmable gain flattening filter **714**, which introduces losses to the most intense channels, thus flattening the power profile over the multiple channels in the fiber **702**. The gain flattening filter **714** may be positioned before or after the amplifier **704**.

The dual transmission diffraction grating device may also be used as an optical add/drop multiplexer (OADM). One such embodiment of an OADM device **800** is illustrated in FIG. **8**. Multiple channel light typically enters the device **800** from a fiber **802**. The separated channels at the light dispersed region **224** are incident on the light handling unit **230** which includes a switch unit **804** containing a number of optical switches **806** for all, or a selected number, of respective channels. Lenses, for example in the form of a microlens array, may be positioned before the optical switches **806**. A control unit **810** is coupled to the switch unit **804** to control the activation states of the switches **806**, thus providing programmability to the OADM device **800**. Each switch **806** is positioned so as to lie on the path of its respective channel. In the particular embodiment shown, the switches **806** are reflection/transmission switches, that either transmit light to associated fibers **808**, or reflect the light back along the path to the fiber **802**.

One particular example of a transmission switch is illustrated in FIGS. **9**A and **9**B. The switch **806** may be a micro-electromechanical system (MEMS) device that includes a traveler **810** that can be moved between a first position, illustrated in FIG. **9**A, and a second position, illustrated in FIG. **9**B. A reflective element **812**, for example a mirror, is attached to the traveler **810**. When the traveler **810** is in the first position, the reflective element **812** occludes the aperture **814** through the switch **806**, and reflects light **816** incident thereon back through the OADM device **800**. The reflective element **812** may retroreflect the light back to the input, in which case the light thus reflected exits the device **800** through the fiber **802**. When the traveler **810** is in the second position, shown in FIG. **9**B, the reflective element **812** is removed from blocking the aperture **814**, and the light is transmitted through the switch **806**. Since each switch **806** is associated with its own channel, the channels may be switched independently to be either transmitted or reflected within the OADM device **800**. Light transmitted through the switch **806** may enter a respective fiber **808** associated with that channel. The switch **806** may be, for example, a sliding mirror switch like the Optical Switch Chip manufactured by Cronos, Research Triangle Park, NC.

An optical arrangement for the OADM device **800** is illustrated in FIG. **10**, that permits the OADM device **800** to operate within a fiber network. Multiple channel light enters the first port **820** of a circulator **822**, exits from the second port **824** of the circulator **822**, and is passed to the OADM

device **800**. The OADM device **800** transmits one or more selected channels and reflects the remaining channels. In the illustration, the OADM device **800** transmits the ith channel, at a wavelength λi, and reflects the remaining channels, at wavelengths λ**0**. . . λi−1, λi+1. . . λm_0. The reflected channels are presented to the second port **824** of the circulator **822** and are output from the third port **826** of the circulator **822**.

The transmitted channels may be passed into a MUX **828**, where they are multiplexed into a single output signal **830**. The MUX **828** may be any suitable type of DWDM device, including a MUX as illustrated in FIG. **2**, placed back to back with the OADM device **800**.

Another embodiment of an OADM **800** is illustrated in FIG. **11**, in which the switch unit **804** includes reflective switches, rather than transmissive switches. In this embodiment, the selected channels are not transmitted out of the light dispersed region **224**, but are reflected along a different path within the OADM **800**, and are typically output at the same end of the OADM **800** as the input.

In this embodiment, a multiple channel signal enters the first port **1102** of a circulator **1104**. The multiple channel signal, for example containing wavelengths λ**0**–λm_0, is transmitted to the OADM device **800** from the second port **1106** of the circulator **1104**. Channels reflected from the OADM device **800** pass back to the second port **1106** of the circulator **1104** and are transmitted out of the third port **1108**. In the illustrated example, the OADM drops the ith channel, at wavelength λi, and reflects all the other channels to the circulator **1104**. The output from the third circulator port **1108** includes wavelengths λ**0**. . . λi−1, λi+1. . . λm_0. The dropped channel, at wavelength λi, or channels, may be directed to a local loop **1110**.

It will be appreciated that the OADM device **800** may be operated in reverse to add a channel. In such a case, the dropped channels may be directed to the local loop **1110** through a circulator **1112**. The circulator **1112** permits the local loop to send information at the dropped channel wavelengths back to the OADM device where they are added to the undropped channels. In such a case, the output from the third port **1108** of the circulator **1104** contains all the undropped channels as well as the channels added from the local loop **1110**.

A cross-section AA' through the device **800** having reflective optical switches is illustrated in FIGS. **12**A and **12**B. In this embodiment, the device **800** includes two separate focusing mirrors **220** and **1122**. Multiple channel light, shown by dashed lines **1124**, from the multiple channel input fiber **802**, is incident on the first mirror **220** and focuses individual channels to their respective switches **806**. The figure shows the separated light **1128** for a single channel (shown in solid lines) being focused by the first mirror **220** to its respective switch **1116**. When the switch **1116** is in a first position, the switch reflects the light **1128** back along the same path, as illustrated in FIG. **12**A. When the switch **1116** is in a second position, as illustrated in FIG. **12**B, the incident light **1128** is directed to the second mirror as deflected light **1130**. The deflected light **1130** is collimated by the second mirror **1122** as deflected, collimated light **1132**, shown by dashed lines.

The deflected, collimated light **1132** passes through the two transmission diffraction gratings **216** and **214**, as selected light beam **1133**. This is shown in FIG. **13**, which schematically illustrates the cross-section BB' of the device **800**. The selected light beam **1133**, containing those channels switched by switches **1116**, is directed from the transmission grating **214** (shown in dashed lines) to a second focusing system **1136**. The second focusing system may include one or more lenses. In the illustrated embodiment, the focusing system includes two lenses **1137** and **1138**. Those channels not selected by the switches **1116** are retroreflected by the switches **1116** along their original paths to the input fiber **802**.

It will be appreciated that the selected light beam **1133** may originate from a reflection from switch **1116** to the second focusing mirror **1122**, or from a reflection from switch **1116** to a region on the focusing mirror **220** that is different from the region illuminated by the beam **1124**.

An embodiment of a reflective switch **1116** that may be used in the OADM illustrated in FIGS. **11**–**13** is illustrated in FIGS. **14**A and **14**B. The switch **1116** may be a MEMs device having a reflecting surface **1118** that can be moved between at least two positions. The reflecting surface **1118** is typically positioned at the focus of the light **1128**. In the first position, illustrated in FIG. **14**A, incoming light **1128** is reflected back along its incident path. In the second position, illustrated in FIG. **14**B, the reflecting surface **1118** is directed so that the incident light **1128** is reflected as deflected light **1130** along a different path from the incident light **1128**.

Another embodiment of a reflecting OADM **800**, in which the OADM **800** includes a single focusing mirror **220** and a collimating/focusing system **206** common to both the input and the selected output, is illustrated in FIGS. **15**A and **15**B, which shows the cross-section AA'. In this particular embodiment, the switches **1516** are placed further away from the mirror **220** than the focus of the light **1528**. Multiple channel light, shown by dashed lines **1124**, from the multiple channel input fiber **802**, is incident on the mirror **220** and focuses individual channels to their respective switches **806**. The figure shows the separated light **1128** for a single channel, solid lines, being focused by the first mirror **220** to its respective switch **1516**. When the switch **1516** is in a first position, the switch **1516** reflects the light **1128** back along the same path, as illustrated in FIG. **15**A. When the switch **1516** is in a second position, as illustrated in FIG. **15**B, the incident light **1128** is directed to the mirror **220** as deflected light **1140** along a different path.

The deflected, collimated light **1140** passes through the two transmission diffraction gratings **216** and **214**, as selected light beam **1142**. This is illustrated in FIG. **16**, which schematically illustrates the cross-section BB' of the device **800**. The selected light beam **1142**, containing those channels switched by switches **1516**, is directed from the transmission grating **214** (shown in dashed lines) to a second focusing system **1143**. The second focusing system may include one or more lenses. In the illustrated embodiment, the first and second focusing systems **206** and **1143** that includes a common lens **1144**. Those channels not selected by the switches **1516** are retroreflected by the switches **1516** along their original paths to the input fiber **802**.

An embodiment of a reflective switch **1516** that may be used in the embodiment of OADM of in FIGS. **15** and **16** is illustrated in FIGS. **17**A and **17**B. The switch **1516** may be a MEMs device having a reflecting surface **1518** that can be moved between at least two positions. The switch may be, for example, a linear MMDM (micromachined deformable mirror) supplied by Flexible Optics BV, Netherlands.

The reflecting surface **1518** is typically positioned beyond the focus of the light **1128**. The reflecting surface **1518** is curved so as to match the radius of the wavefronts of the light from the focus **1520**. In the first position, illustrated in FIG. **17**A, incoming light **1128** passes through the focus **1520** and is reflected back along its incident path. In the

second position, illustrated in FIG. **17**B, the reflecting surface **1518** is directed so that the incident light **1128** is reflected as deflected light **1140** along a different path from the incident light **1128**. The deflected light **1140** passes through a different focus **1522**.

A schematic representation of the unfolded optical path through the OADM device using the switch **1516** is illustrated in FIG. **18**A. The illustrated representation includes a common lens system **1802** for the first and second fibers **1808** and **1820**. Focusing mirror **220** is represented as a lens **1804**. Light passing between the first fiber **1808** and the switch **1516** is represented with solid lines, while light passing between the switch **1516** and the second fiber **1820** is represented by dashed lines. The transmission gratings are omitted from this representation since they have no focusing effect and are located where the beams are collimated.

Input light **1806** is directed to the first lens **1802** from the input fiber **1808**. The input light **1806** is collimated as beam **1810**, and is directed to the second lens **1804**. The second lens **1804** focuses the collimated beam **1810** to the switch **1516** as focused beam **1812**. When the switch **1516** is in the second position, the switch **1516** redirects the focused beam **1812** as redirected beam **1814**. The redirected beam **1814** is collimated by the second lens **1804**, as collimated beam **1816**. The collimated beam **1816** is then focused by the first lens **1802** as focused beam **1818**. The focused beam **1818** is directed to the second fiber **1820**.

For comparison, FIG. **18**B illustrates a schematic representation of the unfolded optical path through the OADM device using the switch **1116**. In this case, the switch is located at the focus of beam **1812**. The input light is collimated by collimating/focusing system **1850** and the light exiting to second fiber **1820** is focused by collimating/focusing system **1852**.

The use of an aspherical focusing optic **220** permits the different optical channels to be focused at the light dispersed region **224** with uniform interchannel spacing. This is useful, for example, where the device **200** is used as a MUX/DMUX, in which case the fiber array **230** may be a standard optical fiber array where the fiber cores are equidistantly spaced apart from each other. It is also useful where the device is used as a channel monitor. The detector unit **604** may be a photodetector sensor array, with a linear array of pixels having uniform width. For example, the center-to-center pixel spacing may be 50 μm. Where each channel is assigned two pixels and the interchannel spacing is 50 GHz (0.4 nm), then the dispersion at the focal plane in the light dispersed region **224** is 500 GHz mm^{-1}. Where a microlens array is positioned before the fiber array **230**, the detector unit **604**, or switches **806**, the center-to-center spacing of the lenses in the lens array may be uniform when the aspherical focusing optic **220** is used.

If the dispersion at the light dispersed region **224** is not uniform, then some channels may take more than two pixels. A plot is shown in FIG. **19** that compares the uniformity of the dispersion at the light dispersed region **224** using spherical optics and aspherical optics. The calculations used to generate FIG. **19** assumed that the device **200** was analyzing light in the range 1530 nm–1565 nm and that the channel separation was 50 GHz (0.4 nm), resulting in 88 channels. Each channel was assigned two pixels, thus ideally the channels are separated in the light dispersed region by 100 μm, corresponding to using transmission gratings **214** and **216** having a period of 1042 nm. In the figure, the y-axis shows the number of times that a channel has shifted more than 50 μm relative to its ideal position as a function of wavelength. The first curve **1902** represents the results when spherical optics are assumed, and curve **1904** shows the results when aspherical optics are assumed. The spherical case shows that the dispersion is quite nonuniform across the light dispersed region **224**, whereas the dispersion is very uniform when aspherical optics are used.

The particular optics assumed to produce the modeled results shown for curve **1904** are shown in FIG. **20**. The aspherical mirror **2020** had an aspheric surface whose sag, Z_m, is given as a function of r, the radial co-ordinate on the mirror, as:

$$z_m(r) = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + a2r^2 + a4r^4 + a6r^6 \ldots + a16r^{16} \tag{2}$$

where, k is the selected conical constant, c is the selected curvature and a**2**–a**16** are the aspherical constants. The values of the various constants used in the model for the aspheric mirror are listed in Table I.

TABLE I

Values for Constants in Model for Aspheric Mirror

constant	value
k	−0.9331551
c	7.4608158×10^{-3} mm^{-1}
a2	7.3167596×10^{-4} mm^{-1}
a4	1.757052×10^{-6} mm^{-3}
a6	$-1.7351298 \times 10^{-8}$ mm^{-5}
a8	$1.34355037 \times 10^{-10}$ mm^{-7}
a10	$-6.0319772 \times 10^{-13}$ mm^{-9}
a12	$1.5372169 \times 10^{-15}$ mm^{-11}
a14	-2.10916×10^{-18} mm^{-13}
a16	$1.21165631 \times 10^{-21}$ mm^{-15}

An aspherical compensator **2022** may also be used to flatten the field at the light dispersed region **224**. The aspherical compensator has an aspherical surface whose sag, Z_c, is given by:

$$z_c(r) = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + b1r + b2r^2 + b3r^3 \ldots + b8r^8 \tag{3}$$

where b**1**–b**8** are the selected aspherical constants. The values of the various constants used in the model for the aspheric compensator are listed in Table II.

TABLE II

Values for Constants in Model for Aspheric Compensator

constant	value
k	−175.6974
c	$15.9511359 \times 10^{-3}$ mm^{-1}
b1	3.366450×10^{-5}
b2	1.4243661×10^{-2} mm^{-1}
b3	$-6.4890499 \times 10^{-5}$ mm^{-2}
b4	$-5.1346641 \times 10^{-5}$ mm^{-3}
b5	$-5.3936903 \times 10^{-6}$ mm^{-4}
b6	$-4.2646931 \times 10^{-7}$ mm^{-5}
b7	$-3.4720059 \times 10^{-9}$ mm^{-6}
b8	9.172209×10^{-9} mm^{-7}

It will be appreciated that an aspheric mirror may used alone, without an aspheric compensator.

Furthermore, a transmissive focusing element, rather than a reflective focusing element, may be used to focus the light from the second grating **216** to the light dispersed region **224**. Such a configuration is illustrated in FIG. **21**. The

illustrated device **2100** has a transmissive focusing element **2120** that focuses the doubly diffracted beam **222** to the light dispersed region **2124**. The transmissive focusing element **2120** may be, for example, a lens or a diffractive focusing optic. The transmissive focusing element **2120** may have either a spherical or an aspherical optical transfer function, to provide spherical or aspherical focusing respectively. The focused light components **2126** are directed to a light handling unit **2130** which may be any device disposed at the light dispersed region **2124** for handling the dispersed light components **2126**, such as a fiber array, a switch array, a detector array, or the like.

It will further be appreciated that if the focusing elements, either mirror or lens system, or a combination, do not produce uniform dispersion at the light dispersed region **2124**, then a fiber array or detector array positioned at the light dispersed region **2124** may itself be non-uniform, having a non-uniformity matching that of the dispersion. Therefore, for example, if the separation between different channels changes from the short wavelength to the long wavelength, then the center-to-center spacing of detector elements in a detector array may increase in a similar manner. Having a non-uniform detector array preserves a constant number of detector elements per channel spacing, even though the different channels are not dispersed linearly across the light dispersed region **2124**. Also, if the light handling device **2130** is a fiber array or a switch array, then the fibers or switches may be arrayed to have non-uniform separation to match the dispersion of the light in the light dispersed region **2124**.

Another embodiment **3400** in which a transmissive focusing element is used to focus the light to the light handling unit **3430** is illustrated in FIG. **34**. In this embodiment, the second transmission grating **3416** is a diffractive element that focuses as well as disperses the light. Therefore, diffracted beams **218** are focused from the transmission grating **3416** to the light handling unit **3430**, illustrated as beam **3422** and beam **3424**. It will be appreciated that more than one of the gratings may both focus and disperse light. For example, the lenses **208** and **210** and transmission grating **214** may be replaced by a grating that collimates and disperses light directly from the fiber **202**.

Another embodiment of a transmission grating add/drop device **2200** is illustrated in FIG. **22**. In this device **2200**, there are three ports for light to either enter or exit. The first port **2202** is an input port for inputting light to the device **2200**. Light reaches the switch array **2204** from the first port **2202** along a first path **2206** after the different channels are separated by being dispersed by the transmission gratings. The switch array **2204** is disposed so that each separated channel has a respective optical switch that selectively reflects or transmits the light of its associated channel. Light transmitted by the switch array is directed through the second port **2208**. The light transmitted through the second port **2208** may be combined in a MUX **2228** into a single combined signal.

Light reflected by the switch array **2204** is directed along a second path **2210** that passes through the transmission gratings. Those channels whose light is reflected by the switch array **2204** are recombined into a single output signal appearing at the third port **2212**. In the illustration, channels having wavelengths $\lambda\mathbf{0}$–λm_0 are directed into the device **2200** through the first port **2202**. The switch array **2204** selects the channel having a wavelength λi for transmission through the second port **2208**, while all other channels are reflected for output from the third port **2212**. Thus, unlike the embodiment illustrated in FIG. **10**, this embodiment does not require the use of a circulator to separate the input from the reflected output. It will be appreciated that the switch array **2204** may select any combination of one or more channels for transmission.

Although internal details of this embodiment are not expressly included in the figure, it will be appreciated that any of the add/drop multiplexer configurations described herein may be adapted to produce a three port add/drop device.

Another embodiment of a transmission grating add/drop device **3100** is illustrated in FIG. **31**. In this device **3100**, there are several ports for light to enter or exit. The first port **3102** is an input port for inputting light to the device **3100**. Light reaches the switch array **3104** from the first port **3102** along a first path **3106** (solid line) after the different channels are separated by being dispersed by the transmission gratings. The switch array **3104** is disposed so that each separated channel has a respective optical switch **3108** that selectively reflects the light of its associated channel into one of a number of different directions.

An embodiment of a switch having multiple states is illustrated in FIG. **32**. The switch **3108** has a reflector **3202** that is selectively movable among several different positions. In the particular embodiment illustrated, the reflector **3202** is pivotable among four different positions: one position is illustrated as a solid line, and the other positions **3206** are illustrated with dashed lines. It will be appreciated that the switch may be selectively adjustable between a number of positions that is different from four.

The light reflected by the switch array **3104** is directed back through the transmission gratings. The switches **3108** are selectively operable between a number of positions, four in the illustrated embodiment, that correspond to different paths **3110**, **3112**, **3114** and **3116** coupled to respective selected channel ports **3120**, **3122**, **3124** and **3126**. Thus, each channel may be independently switchable to a number of different output ports through selective positioning of the respective switches **3108**. In the illustration, the switch **3108** is in a position to direct light along path **3112**, shown in solid line, to port **3122**. The other possible paths **3110**, **3114** and **3116** are shown in dashed line.

An unfolded, equivalent optical architecture for the device **3100** is illustrated in FIG. **33**. Light **3304** enters the device **3100** through a first fiber **3302** and is collimated in a first collimating unit **3306**. The collimated beam **3308** passes through the transmission gratings (not shown) to the focusing optic **3310**, which directs the focused beam **3312** to the switch array **3104**. The switch array **3104** directs each channel along a particular selected reflected path. Only one channel is illustrated in the figure. The channel is reflected along path **3112**, that corresponds to the path traveled by the diverging beam **3314**, collimated by the focusing optic **3310** to produce collimated beam **3316**, and collimated beam **3316** which is focused into fiber **3318** by focusing system **3320**.

The switch **3108** is selectable among other paths, **3110**, **3114** and **3116** that correspond to light beams **3330**, **3334** and **3336**, illustrated in dashed lines, that are directed to respective fibers **3340**, **3344** and **3346** by respective focusing systems **3350**, **3354** and **3356**. Thus, the device **3100** permits selective switching of different channels into different outputs, and may be regarded as being a multiple output drop filter.

It will be appreciated that light may be directed into the device **3100** in the reverse direction, so that light entering the device **3100** from ports **3120**, **3122**, **3124** and **3126** is combined into an output signal that exits the device from

port **3102**. In such a case, the device **3100** operates as a multiple input add filter. Furthermore, light input to the device from ports **3120**, **3122**, **3124** and **3126** need not be directed to port **3102** but, so long as the switches **3108** provide suitable selectivity, may be directed to any of the other ports.

The invention is not restricted to using only two diffraction gratings, and other numbers of gratings may be used. Another embodiment of a transmission grating WDM device **2300** is illustrated in FIG. **23**, which uses three gratings. An advantage of using additional gratings is that, where the grating period is constant, the dispersion is increased and so effective channel separation may be achieved in a smaller device.

Following diffraction off the first two gratings **214** and **216**, the doubly-dispersed light **222** is directed to a third grating **2315** that diffracts the light, as triply diffracted light **2322**, towards a light focusing element **2320**, illustrated in this case as a lens. It will be appreciated that the light focusing element **2320** my also be any other suitable type of focusing element. Individually focused wavelength components **2326** are directed to the light dispersed region **2324** where they are spatially separated from each other. The focused light components **2326** are directed to a light handling unit **2330** which may be any device disposed at the light dispersed region **2324** for handling the dispersed light components **2326**, such as a fiber array, a switch array, a detector array, or the like. It will be appreciated that other numbers of transmission gratings may be used, other than two or three.

Some diffraction gratings display higher diffraction efficiency for TE polarized light than for TM polarized light, and so the total diffraction efficiency may be reduced if randomly polarized light is transmitted into the device. Therefore, it is advantageous to use polarization dependent components within the device in order to increase the total diffraction efficiency. One embodiment of such a device **2400**, schematically illustrated in FIG. **24**, includes a polarization separator **2410**, which may include a polarizing beamsplitter or other suitable component for separating randomly polarized light into its orthogonal polarization states.

Light **2402** from the fiber **202** is randomly polarized, and is collimated in the focusing/collimating system **206**. The collimated light enters the polarization separator **2410**, which in the illustrated embodiment includes a polarization beamsplitter **2412** and a turning prism **2414**. A first polarization component **2416** is transmitted through the polarization beamsplitter **2412** along a first path **2420** (illustrated with solid lines). A second polarization component **2418**, having a polarization state orthogonal to the polarization state of the first polarization component, is reflected from the polarization beamsplitter **2412** to the turning prism **2414**. The turning prism **2414** reflects the second polarization component **2418** along a second path **2422** (illustrated with dashed lines) approximately parallel to the first path **2420**. A polarization rotator **2424**, such as a half-wave retardation plate, is disposed on one of the paths **2420** and **2422** to rotate the polarization of that path through approximately 90°, so that the polarization of the light propagating along both paths **2420** and **2422** is parallel, and oriented in the preferred polarization state for maximum diffraction efficiency in the transmission gratings **214** and **216**.

In the embodiment illustrated in FIG. **24**, it has been assumed that only one wavelength of light enters the device **2400**, for the sake of clarity. The light propagating along the first and second paths **2420** and **2422** propagates approximately parallel through the first and second gratings **214** and **216** until reaching the focusing mirror **220**. The focusing mirror **220** focuses the light in the two paths **2420** and **2422** to the same focus **2426** at the light handling unit **2430**. This embodiment is particularly useful when the light handling unit **2430** includes photodetectors to detect the power of the light in the different channels.

Another embodiment of the device **2800** that considers that polarization of the light is schematically illustrated in FIG. **28**. The device **2800** includes a polarization separator **2410** similar to that illustrated in FIG. **24**. In FIG. **24**, the polarization states are separated in a direction that is in the diffraction plane, in other words parallel to the plane defined by the directions of diffraction of gratings **214** and **216**. In the embodiment **2800** illustrated in FIG. **28**, the direction of separation is perpendicular to the plane of diffraction. Thus, light entering through fiber **202** is separated into two beams of orthogonal polarization that are spaced out of the plane of the figure. A polarization rotator **2424** rotates the polarization of one of the beams to an orientation that results in high diffraction efficiency in the gratings **214** and **216**.

After diffraction by the gratings **214** and **216**, the beams **2420** and **2422** are combined in a polarization combiner **2802** before incidence on the mirror, as is schematically illustrated in FIG. **29**. The polarization combiner **2802** includes a polarization rotator **2804** to rotate the polarization of one of the beams **2420** and **2422** through 90°. Beam **2422** is directed by a turning prism **2806** into a polarization beamsplitter **2808**, which combines the two beams **2420** and **2422** into a randomly polarized beam **2810**, which then passes to the mirror **220**. This embodiment is particularly useful when the device **2800** operates as a MUX, DMUX, or add/drop multiplexer.

It will be appreciated that different types of polarization separator **2410** and polarization combiner **2802** may be employed, in addition to those illustrated in the drawings. Furthermore, it will be appreciated that the polarization separator **2410** and polarization combiner **2802** perform the reverse optical operation when light passes through the device **2800** in reverse. Thus, light passing from the light handling device **2430** to the multiple channel fiber **202** is polarization separated in the polarization combiner **2802** and is polarization combined in the polarization separator **2410**.

Another approach to ensure high diffraction efficiency when the device is used with randomly polarized light is to use gratings that provide high diffraction efficiency for both the incident TE and TM polarizations. For example, it is possible to design a transmission grating so that the diffraction efficiency of both polarizations is substantially equal, as is discussed in U.S. patent application Ser. No. 09/789,888, entitled "Grating structures and Methods of Making the Grating Structures", filed on Feb. 21, 2001 and naming J. Holm, H. Madsen, S. Weichel, P. E. Isben and B. Rose as inventors.

In another approach, the gratings **214** and **216** may be replaced by dual grating pairs **3214** and **3216**, where each member of the pair is optimized for high diffraction efficiency for a single polarization, as is schematically illustrated in FIG. **30**. A beam **3002** of mixed polarization, having both TE and TM components, or of random polarization, is incident on a first grating **3214***a* of the first dual grating pair **3214**, which is optimized for high diffraction efficiency for TM light, and zero diffraction efficiency for TE light. Thus, the TE light passes through the grating **3214***a* as beam **3004** while the TM light is diffracted as beam **3006**. The TE beam **3004** is then diffracted by the second grating **3214***b* of the dual grating pair **3214** which is optimized for high diffraction efficiency of TE light, as beam **3008**.

The TE beam **3008** is then diffracted by the first grating **3216***a* of the second dual grating pair **3216** as beam **3010**. The grating **3216***a* is optimized for high diffraction efficiency for TE light. The TE beam **3010** passes through the second grating **3216***b* of the second dual grating pair **3216**, which is optimized for high diffraction efficiency for TM light and zero diffraction for TE light. The TM beam **3006** is diffracted by the second grating **3216***b*. Careful alignment of the gratings **3214***a*, **3214***b*, **3216***a* and **3216***b* results in the TE beam **3101** being combined with the TE beam **3006** to produce a diffracted beam **3012** of mixed polarization.

It will be appreciated that dual grating approach may be used in any of the embodiments described above. Furthermore, the dual grating approach may be used in devices having more than two dual grating pairs.

An embodiment of a housing for mounting the different components of a double transmission diffraction grating device is illustrated in FIGS. **25**A and **25**B. The housing **2500** includes a frame **2502** having upper and lower rails **2504** and **2506** with slots **2508** running thereacross. The upper rail **2504** and lower rail **2506** are provided with complementary slots forming slot pairs, where each slot pair is aligned to receive a mounting plate **2510**. The various optical components of the device are mounted on different mounting plates **2510** that fit into the slots **2508**. Precise positioning of the slots along the rails and of the optical components on the plates permits the device to be assembled with components in alignment, without the need for optical alignment of the optical components after assembly. The ability to assemble the optical system without aligning the optical components after assembly is termed passive alignment. The frame and slots may be machined, for example, from aluminum, stainless steel, or any other suitable material.

Optical components are mounted on the plates **2510**, for example using epoxy adhesive. In the particular embodiment illustrated, the first lens **208** is mounted on a first plate **2512**. The first plate **2512** is provided with an aperture **2514** over which the lens **208** is mounted, so as to permit the light to enter the device **2500**. The second lens **210** is mounted on a second plate **2514**, also provided with an aperture **2516**. In general, transmissive optical components are mounted over apertures in the plates to permit light to pass therethrough.

The transmission diffraction gratings **214** and **216** are positioned on a plate **2518** that has angled surfaces **2520** and **2522** upon which the respective gratings **214** and **216** are mounted. An aperture **2524** permits light to pass between the gratings **214** and **216**. Another aperture **2526** permits the passage of light from the mirror **220** to the light dispersed region **224**.

The mirror **220** is mounted on another plate **2528**. The plate **2528** includes an aperture **2530** to permit passage of the beam **212** from the second lens **210**. In general, plates carrying both transmissive and reflective optical components may be provided with apertures to permit passage of light through a part of the plate where the optical component is not mounted. An advantage of this construction is that the plates block stray light from propagating within the device, which is particularly advantageous when the device is used as a monitor and low light levels are being detected.

A plate **2510** is illustrated in FIG. **25**B. The plate has parallel upper and lower edges **2552** and **2554**. The plate **2510** is provided with an aperture **2556** in an area **2558** that may be countersunk by machining or etching to receive an optical component.

It will be appreciated that, rather than sliding the plates into slots along upper and lower edges, the frame may have slotted members on the sides, and the sides of the plates fit into the slots on the slotted members.

It will also be appreciated that the position of the slots **2508** along the frame **2502** is dependent on the optical properties of the system and the particular component carried by the particular plate to be placed within the slots. The position may be determined theoretically, experimentally, or both. The accurate positioning of the slots **2508** and the accuracy of replication of the determined slot positions influences the ability to passively align the optical components. In addition, it may be important that the frames fit snugly into their respective slots to reduce or minimize the amount of variability in the position of the optical components.

Another embodiment of a housing **2600** for mounting the different components of a double transmission diffraction grating device is illustrated in FIG. **26**. An integral frame **2602** holds the gratings **214** and **216**, and the focusing mirror **220**. The integral frame **2602** may be machined from metal, such as aluminum or stainless steel, or may be precision injection molded using a plastic material. The input fiber **2604** is coupled to a collimation unit **2606**, which includes one or more lenses to collimate the light from the fiber **2604**. The collimation unit **2606** is positioned in the integral frame **2602** to direct collimated light to the first transmissive diffraction grating **214**. The integral frame **2602** is fabricated to be free of obstructions along the optical path between the collimation unit **2606** and the light handling unit **2630**. The collimation unit **2606** may be provided with a polarization separator in a manner similar to that illustrated in FIG. **24**.

The light handling unit **2630** may be disposed on a plate **2608** attached to the integral frame **2602** via screws or other suitable method. Independent attachment of the plate **2608** provides a degree of adjustability in the alignment of the light handling unit **2630** relative to the separated channels incident at the light dispersed region **2624**. The light handling unit **2630** may be any device that operates on the separated channels incident at the light dispersed region **2624**, such as a detector array (illustrated), a fiber array or a light switch array.

In this embodiment, and in the other monitor embodiments described above, the detector array **2632** may be a uniform photodetector array or may be an array with varying spacing between the individual detectors.

A perspective view of the device **2600** is illustrated in FIG. **27**, showing the external features of the integral frame **2602**. The plate **2608** has a number of output pins **2634** that permit connection of the detector electronics to an external device, such as a monitor or processor. The sides of the integral frame **2602** are covered with side covers **2636**, at least one of which is detachable for access for mounting components within the integral frame **2602**. One of the covers **2636**, on the other hand, may be formed integral to the integral frame **2602**.

An approach to providing monitoring and data analysis capabilities to the a device having an integral frame is schematically illustrated in FIGS. **35**A and **35**B. An electronics package **3500** is illustrated in FIG. **35**A, that includes a detector array **3502**, for example a photodiode array, mounted on a substrate **3504**. The substrate **3504** is electrically coupled to a board **3506**, for example a printboard, that contains electronics for controlling the detector array **3502** and for analyzing detection signals produced by the detector array **3502**. The substrate **3504** and board **3506** may be coupled by a flexible link **3508**, using, for example, flexprint. The board **3506** may include connection pads **3509** for forming an electrical connection to external circuits, for example power supply or data collection and analysis circuits.

The electronics package **3500** is illustrated in use with an embodiment of integral body **3510** in FIG. **35**B. The integral frame **3510** may include transmission diffraction gratings, along with focusing and collimating optics, as was described with reference to FIG. **26**. A fiber **3513** may be coupled to the collimation unit **3512** to input light to the integral frame **3510**. The board **3506** is placed on one side of the integral frame **3510**, with the detector array **3502** positioned at the output end **3512** of the integral frame **3510** to detect the dispersed light beams. The flexible link **3508** permits the detector array **3502** to be positioned at the end of the integral frame **3510** while the board **3506** is positioned along the side of the integral body **3510**, thus saving space. The board **3506** and substrate **3504** may be attached to the integral frame **3510** using, for example, screws, epoxy or some other type of fastening (not shown).

A cover **3514** may be attached to the integral frame **3510** to provide protection to the board **3506**. The cover **3514** may include electrical conduits **3516** that connect through the cover **3514** to the connection pads **3509**. The conduits **3516** may be pins that coupe to the connection pads **3509** by pressure, for example using spring-bias. In another approach (not illustrated), the board **3506** may be provided with electrical connectors that protrude through apertures in the cover **3514**. The cover **3514** may be attached to the integral frame **3510** using any suitable method, including screws or other fasteners, soldering, welding or adhesive. An o-ring seal may be provided between the cover **3514** and the integral frame **3510** to prevent the ingress of dust, particles and other contaminants to the integral frame **3510**. A second cover **3518** may be provided on the other side of the integral frame **3510** to provide easy access within the integral frame **3510** for mounting optical components.

Another embodiment using an integrated frame **3510** is illustrated in FIG. **35**C. In this embodiment **3500**, a light handling unit **3530**, which may be, for example, a detector array or optical switch array, is attached to one end **3512** of the integrated frame **3510**. Electronic circuits **3526** and **3527** may be positioned on either side of the integrated frame **3510**. The electronic circuits **3526** and **3528** may be coupled to the light handling unit **3530** by flexible connectors **3528** and **3529**. Covers **3514** and **3532** on either side of the integral frame **3510** may be provided to protect the electronic circuits **3526** and **3527** and to prevent ingress of contaminants to the optical components mounted on the integral frame **3510**.

It is important to note that the invention is not limited to the embodiments illustrated in the figures described above, and that certain elements may be changed without exceeding the scope of the invention. For example, planar waveguides may be used instead of either the multiple channel fiber **202** or the single channel fibers **232** input fiber, along with suitable coupling optics to adapt the light propagating to and from the waveguides.

As noted above, the present invention is applicable to DWDM optical communications systems, and is believed to be particularly useful for use in MUX/DMUX, channel monitoring, and OADMs. The present invention should not be considered limited to the particular examples described above, but rather should be understood to cover all aspects of the invention as fairly set out in the attached claims. Various modifications, equivalent processes, as well as numerous structures to which the present invention may be applicable will be readily apparent to those of skill in the art to which the present invention is directed upon review of the present specification. The claims are intended to cover such modifications and devices.

We claim:

1. A wavelength division multiplexing device, comprising:

a first multiple channel port;

a plurality of single channel ports;

and a diffraction unit disposed along an optical path defined between the first multiple channel port and the plurality of single channel ports, the diffraction unit including at least:

a first transmissive diffraction element for receiving a beam on the optical path and forming a first spectrally divergent beam on the optical path; and

a second transmissive diffraction element separated from the first transmissive diffraction element for receiving the first spectrally divergent beam on the optical path and forming a second spectrally divergent beam on the optical path having more spectral divergence than the first spectrally divergent beam.

2. A device as recited in claim **1**, further comprising a first light focusing unit disposed on the optical path between the first multiple channel port and the diffraction unit.

3. A device as recited in claim **2**, wherein the first light focusing unit includes one or more lenses.

4. A device as recited in claim **3**, wherein the first light focusing unit includes a spatial filter to spatially filter light entering the device from the first multiple channel port.

5. A device as recited in claim **2**, wherein the first light focusing unit substantially collimates light propagating from the first multiple channel port towards the plurality of single channel ports.

6. A device as recited in claim **1**, further comprising a second light focusing unit disposed on the optical path between the diffraction unit and the plurality of single channel ports.

7. A device as recited in claim **6**, wherein the second light focusing unit is a curved mirror.

8. A device as recited in claim **7**, wherein the curved mirror is an aspheric mirror.

9. A device as recited in claim **8**, further comprising a transmissive aspheric compensator disposed between the aspheric mirror and the plurality of single channel ports.

10. A device as recited in claim **6**, wherein the second light focusing unit indudes a transmissive focusing element.

11. A device as recited in claim **10**, wherein the transmissive focusing element includes an aspheric lens.

12. A device as recited in claim **1**, wherein the diffraction unit includes at least a third transmissive diffraction element disposed on the optical path between the first multiple channel port and the plurality of single channel ports.

13. A device as recited in claim **1**, wherein at least one of the first and second transmissive diffraction elements has a diffraction efficiency for TE polarization having a value that is within less than 10% of a value of diffraction efficiency for TM polarization.

14. A device as recited in claim **1**, wherein at least one of the first and second transmissive diffraction elements includes an encapsulated diffractive structure on a substrate.

15. A device as recited in claim **1**, wherein at least one of the first and second transmisslve diffraction elements includes a first substrate having a first diffractive structure on a first surface and a second substrate having a second diffractive structure, a mirror image of the first diffractive structure, on a second surface, the first surface of the first substrate being attached to the second surface of the second substrate with the first diffractive structure aligned to the second diffractive structure.

16. A device as recited in claim **1**, wherein at least one of the first and second transmissive diffraction elements includes a linear grating.

17. A device as recited in claim **1**, wherein at least one of the first and second transmissive diffraction elements includes a grating having a groove spacing that is nonuniform across the grating.

18. A device as recited in claim **17**, wherein the at least one of the first and second transmissive diffraction elements both focuses and diffracts light.

19. A device as recited in claim **1**, wherein at least one of the first and second transmissive diffraction elements includes a first diffractive segment having a high diffraction efficiency for a first polarization and a diffraction efficiency of approximately zero for a second polarization orthogonal to the first polarization, and a second diffractive segment, parallel to the first diffractive segment, having a high diffraction efficiency for the second polarization.

20. A device as recited in claim **19**, wherein, when randomly polarized light is incident on the first diffractive segment, the first diffractive segment diffracts a first diffracted beam of light of the first polarization in a first direction and transmits light of the second polarization, and the second diffractive segment diffracts a second diffracted beam of light of the second polarization in a direction substantially parallel to the first direction, the first diffractive segment being spaced apart from the second diffractive segment so that the second diffractive segment is positioned clear of the first diffracted beam.

21. A device as recited in claim **1**, further comprising a polarization separation unit disposed between the first multipie channel port and the diffraction unit to separate light entering the device from the first multiple channel port into first and second polarization components having mutually orthogonal polarizations.

22. A device as recited in claim **21**, wherein the polarization separation unit includes a polarization rotator disposed on a path of at least one of the polarization components to rotate polarization of the at least one of the polarization components so as to parallelize polarizations of the first and second polarization components.

23. A device as recited in claim **21**, wherein the polarization separation unit includes beam steering optics to direct the first and second polarization components towards the diffraction unit along substantially parallel paths.

24. A device as recited in claim **21**, further comprising a polarization combining unit disposed between the diffraction unit and the plurality of single channel ports.

25. A device as recited in claim **24**, wherein the polarization combining unit includes a polarization rotator to rotate polarization of one of the polarization components relative to the other polarization component and beam steering optics to combine the first and second polarization components.

26. A device as recited in claim **21**, wherein the first and second polarizations are separated in a plane of diffraction of the device.

27. A device as recited in claim **21**, wherein the first and second polarizations are separated in a direction out of a plane of diffraction of the device.

28. A device as recited in claim **1**, further comprising a multiple channel waveguide coupled to the first multiple channel port.

29. A device as recited in claim **1**, further comprising single channel waveguides coupled to respective single channel ports of the plurality of single channel ports.

30. A device as recited in claim **1**, further comprising an array of single channel waveguides coupled to respective single channel ports of the plurality of single channel ports.

31. A device as recited in claim **30**, wherein spacings between adjacent waveguides are uniform across the array.

32. A device as recited in claim **30**, wherein spacings between adjacent waveguides vary across the array.

33. A device as recited in claim **30**, further comprising an array of focusing elements, focusing elements of the array of focusing elements disposed in relationship to respective single channel waveguides of the array of single channel waveguides, the focusing elements focusing light received from the diffraction unit into respective single channel waveguides.

34. A device as recited in claim **1**, wherein multiple channel light propagates from the first multiple channel port to the plurality of single channel ports.

35. A device as recited in claim **1**, wherein light propagates from single channel ports of the plurality of single channel ports to the first multiple channel port.

36. A device as recited in claim **1**, further comprising photodetectors positioned at respective single channel ports of the plurality of single channel ports.

37. A device as recited in claim **36**, wherein the photodetectors are individual photodetectors.

38. A device as recited in claim **36**, wherein the photodetectors form an integrated photodetector array.

39. A device as recited in claim **36**, further comprising a signal analysis unit coupled to receive detection signals from the photodetectors and to analyze the received detection signals.

40. A device as recited in claim **36**, wherein a spacing between adjacent photodetectors is uniform.

41. A device as recited in claim **36**, wherein a spacing between adjacent photodetectors is nonuniform.

42. A device as recited in claim **1**, further comprising optical switches positioned at respective single channel ports of the plurality of single channel ports.

43. A device as recited in claim **42**, wherein a spacing between adjacent switches is uniform.

44. A device as recited in claim **42**, wherein a spacing between adjacent switches is nonuniform.

45. A device as recited in claim **42**, further comprising a control unit coupled to control activation of the optical switches.

46. A device as recited in claim **42**, wherein at least one of the optical switches has at least first and second operative states, the at least one of the optical switches reflecting light that has propagated from the first multiple channel port in the first operative state.

47. A device as recited in claim **46**, wherein in the first operative state, the at least one of the optical switches reflects light that has propagated from the first multiple channel port back to the first multiple channel port.

48. A device as recited in claim **46**, wherein in the first operative state, the at least one of the optical switches reflects light between the first multiple channel port and a second multiple channel port.

49. A device as recited in claim **48**, wherein, in the second operative state, the at least one of the optical switches reflects light between the first multiple channel port and a third multiple channel port.

50. A device as recited in claim **49**, wherein the at least one optical switch has at least a third operative state, the at least one optical switch reflecting light between the first multiple channel port and a fourth multiple channel port when in the third operative state.

51. A device as recited in claim **48**, further comprising a first focusing system on the wavelength-dependent light paths between the first multiple channel port and the diffraction unit to collimate light entering the device from the first multiple channel port, and a second focusing system,

separate from the first focusing system, disposed to focus light reflected from the optical switches to the second multiple channel port.

52. A device as recited in claim **51**, further comprising a third focusing system between the diffraction unit and the optical switches, light reflected by the optical switches in the first and second operative states being focused by at least one common focusing element of the third focusing system.

53. A device as recited in claim **48**, further comprising a third focusing system on the wavelength-dependent light paths between the first multiple channel port and the diffraction unit and on light paths between the diffraction unit and at least the second multiple channel port, at least one focusing element of the third focusing system being common to light paths of the first and second multiple channel ports.

54. A device as recited in claim **53**, further comprising a fourth focusing system between the diffraction unit and the optical switches, the fourth focusing system having at least one light focusing element to focus light from the diffraction unit to the optical switches, light reflected by the optical switches being incident on the at least one focusing element irrespective of operative states of the optical switches.

55. A device as recited in claim **46**, wherein, in the second operative state, the at least one of the optical switches transmits the light that has propagated from the first multiple channel port.

56. A device as recited in claim **55**, further comprising a wavelength multiplexer coupled to the single channel ports to produce a multiplexed output signal from light transmitted through the at least one of the optical switches.

57. A device as recited in claim **42**, wherein the optical switches are disposed at respective focus points of light propagating from the diffraction unit to the plurality of single channel ports.

58. A device as recited in claim **42**, wherein the optical switches are disposed beyond respective focus points of light propagating from the diffraction unit to the plurality of single channel ports.

59. A device as recited in claim **42**, wherein the optical switches include flat reflective surfaces.

60. A device as recited in claim **42**, wherein the optical switches include curved reflective surfaces.

61. A device as recited in claim **1**, wherein the diffraction unit and a focusing system to focus light from the diffraction unit to the single channel ports are mounted in an integral frame.

62. A device as recited in claim **61**, further comprising a collimation unit mounted in the integral frame, the collimation unit including one or more lenses to collimate light entering the multiple channel port from a multiple channel waveguide.

63. A device as recited in claim **61**, further comprising a light handling unit disposed at a first end of the integral frame, proximate the single channel ports, to detect light from the diffraction unit.

64. A device as recited in claim **63**, further comprising a first electronic circuit for controlling operation of the light handling unit, the first electronic circuit being mounted on at least a first side of the integral frame and coupled to the light handling unit array by a flexible electronic coupling.

65. A device as recited in claim **64**, further comprising a second electronic circuit mounted on a second side of the integral frame opposite the first side.

66. A device as recited in claim **64**, further comprising a cover over the first electronic circuit, electrical conduits passing through the cover to connectors on the electronic circuit.

67. An optical communications system, comprising:
- an optical transmitter, the optical transmitter transmitting a multiple channel communications signal;
- an optical receiver to detect optical signals carried in multiple optical channels;
- a fiber-optic communications link coupled to transport the multiple channel communications signal from the optical transmitter to the optical receiver;
- wherein one of the optical transmitter, the optical receiver and the fiber-optic communications link includes a multiple wavelength device having
- a first multiple channel port;
- a plurality of single channel ports;
- and a diffraction unit disposed along an optical path defined between the first multiple channel port and the plurality of single channel ports, the diffraction unit including at least:
  - a first transmissive diffraction element for receiving a beam on the optical path and forming a first spectrally divergent beam on the optical path; and
  - a second transmissive diffraction element separated from the first tranamissive diffraction element for receiving the first spectrally divergent beam on the optical path and forming a second spectrally divergent beam on the optical path having more spectral divergence than the first spectrally divergent beam.

68. A system as recited in claim **67**, wherein the multiple wavelength device is coupled to receive light from the fiber-optic communications link and includes photodetectors disposed at respective single channel ports.

69. A system as recited in claim **68**, further comprising one or more fiber amplifier units disposed along the fiber-optic communications link, and the multiple wavelength device is coupled to receive light after being amplified in one of the fiber ampiifier units.

70. A system as recited in claim **69**, further comprising a signal analysis unit coupled to receive detection signals from the photodetectors and to analyze the received detection signals.

71. A system as recited in claim **70**, further comprising an amplifier control unit coupled to receive an analyzed detection signal from the signal analysis unit and coupled to the fiber amplifier unit to control gain flatness of the fiber amplifier unit.

72. A system as recited in claim **71**, wherein the amplifier control unit adjusts at least one of pump laser power and pump laser wavelength of the fiber amplifier unit in response to the analyzed detection signal.

73. A system as recited in claim **71**, wherein the amplifier control unit adjusts attenuation for one or more channels in a gain flattening filter in the fiber amplifier unit.

74. A system as recited in claim **67**, wherein the first multiple channel port of the multiple wavelength device is coupled to receive light from the fiber-optic communications link and further comprising an optical cross-connect unit coupled to receive light transmitted from the single channel ports of the multiple wavelength device.

75. A system as recited in claim **74**, further comprising another multiple wavelength device having single channel parts coupled to receive light from the optical cross-connect unit and having a first multiple channel port coupled to direct the light form the optical cross-connect unit into the fiber-optic communications link.

76. A system as recited in claim **67**, wherein the multiple wavelength device is disposed within the optical transmitter, light from lasers operating at different wavelengths being

coupled to the single channel ports to be multiplexed in the multiple wavelength device, the multiple channel communications signal being output from the first multiple channel port.

77. A system as recited in claim **67**, wherein the multiple wavelength device is disposed within the optical receiver, the multiple channel communications signal being coupled into the multiple wavelength device at the first multiple channel port, and single channel detectors being coupled to receive light from respective single channel ports.

78. A system as recited in claim **67**, wherein the multiple wavelength device includes optical switches positioned at respective single channel ports of the plurality of single channel ports, the optical switches having at least a first operative state and a second operative state, the multiple channel communications signal being transmitted into the multiple wavelength device through the first multiple channel port and selected optical switches being activated into different operative states so as to select one or more respective channels to be separated out from the multiple channel communications signal.

79. A system as recited in claim **78**, wherein the multiple channel communications signal is separated into individual channels by the diffraction unit, and the optical switches direct the individual channels to selected ones of at least second and third multiple channel ports.

80. A system as recited in claim **78**, further comprising a circulator having at least first, second and third circulator ports, the first circulator port coupled to pass light from a local loop off the fiber optical communications link to a second circulator port coupled to the second multiple channel port of the multiple wavelength device, the second circulator port being coupled to pass light received from the second multiple channel port of the multiple wavelength device to the local loop.

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